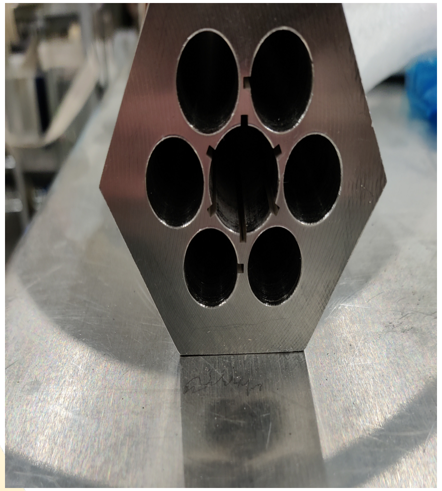
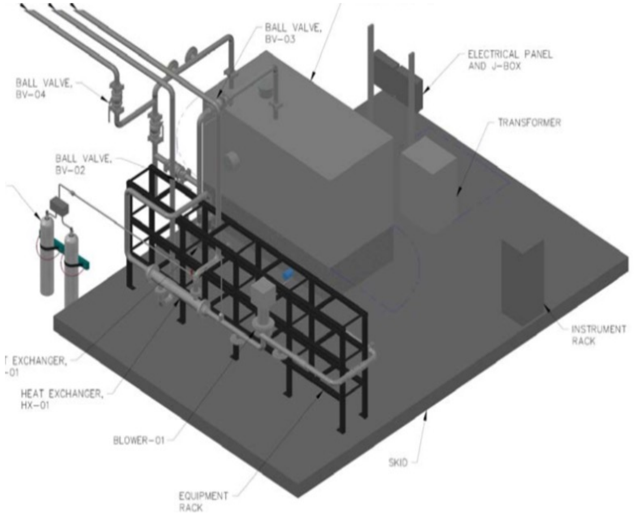
DOE-NE Microreactor Program Winter Review Meeting

Demonstration Capabilities Overview





March 4, 2022

Piyush Sabharwall, Ph.D. | Technical Area Lead

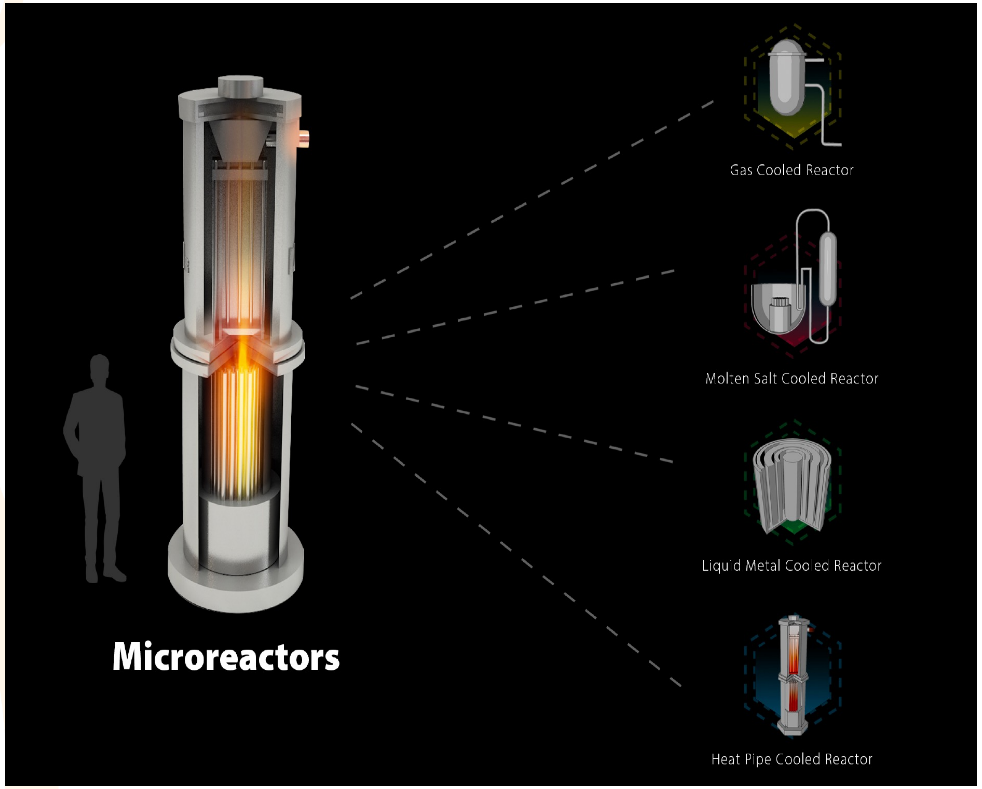
Technical Area Overview

Demonstration Capabilities Technical Area includes two major R&D activities:

Non-Nuclear Testing and Demonstration:

- Single Primary Heat Extraction and Removal Emulator (SPHERE)

- Microreactor AGile Nonnuclear Experiment Testbed (MAGNET)



Team at INL: Piyush Sabharwall, TJ Morton, Helen Guymon, Jeremy Hartvigsen, Zachary Sellers, Troy Unruh, JunSoo Yoo, Donna Guillen, Sunming Qin, and Minseop Song.

Idaho National Laboratory

Los Alamos NATIONAL LABORATORY EST. 1943

OAK RIDGE National Laboratory

MRP Microreactor Program

Demonstration Support Capabilities – Subdivided into 4 main areas to support testing needs to deploy microreactors.

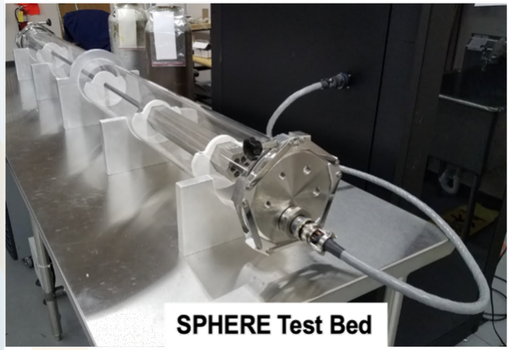
- Single Primary Heat Extraction and Removal Emulator (SPHERE) – Development of a platform to support non-nuclear thermal and integrated systems testing capabilities. This capability shall provide a better understanding of thermal performance of the heat pipe under a wide range of heating values and operating temperatures, further enhancing the understanding of heat pipe during startup, shutdown and transient operation.
- Microreactor Agile Non-nuclear Experimental Testbed (MAGNET) – Development of a thermal-hydraulic and integrated systems testing capability, called the MAGNET, to simulate core thermal behavior, heat pipe and primary heat exchanger performance, and passive decay heat removal will support verification and validation of detailed microreactor thermal hydraulic models. This is applicable under startup, shutdown, steady-state, and off-normal transient behavior in steady-state operation, transient operation, and load-following conditions. This testing is to be done in advance of nuclear system demonstration. The test bed will ultimately be integrated into the broader INL Systems Integration Laboratory, which includes thermal and electrical energy users such as steam electrolysis, real-time digital simulators for power systems emulation, a microgrid test bed, and renewable energy generation.
- Evolving Demonstration Support – Demonstration and testing infrastructure needs are expected to evolve as technology readiness of microreactors advance. Development of capability necessary to support this evolution is covered under this sub-area. Currently, MAGNET is undergoing modifications to support component testing for gas cooled systems.
- Verification and Validation Support – This subarea focuses on targeted testing to support verification and validation to meet industrial needs and licensing organization (such as NRC) needs to enhance understanding of a phenomenon of interest and reduce uncertainty.

MRP Microreactor Program

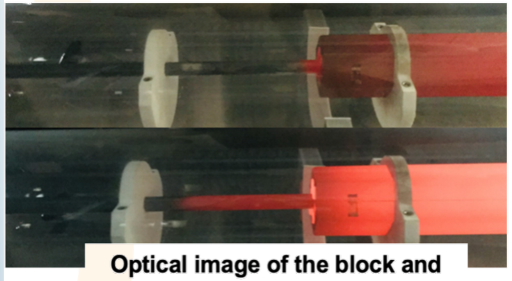
Single Primary Heat Extraction and Removal Emulator (SPHERE)

- Provide capabilities to perform steady state and transient testing of heat pipes and heat transfer:
  - Wide range of heating values and operating temperatures
  - Observe **heat pipe startup and transient operation**
- **Develop** effective thermal coupling methods between the heat pipe outer surface and core structures
- **Measure** heat pipe axial temperature profiles during **startup, steady-state, and transient operation** using thermal imaging and surface measurements

Parameter	Value
Length	243 cm
Diameter	15 cm
Tube material	Quartz
Connections	Flanged for gas flow and instrumentation feed through
Maximum power	20 kW
Max Temperature	750 C
Heat Removal	Passive radiation or water-cooled gas gap calorimeter



SPHERE Test Bed



Optical image of the block and heat pipe operation

Key Accomplishments

- SPHERE Initial Startup and Operation
- Complete Engineering Design of Gap Conductance Test Article

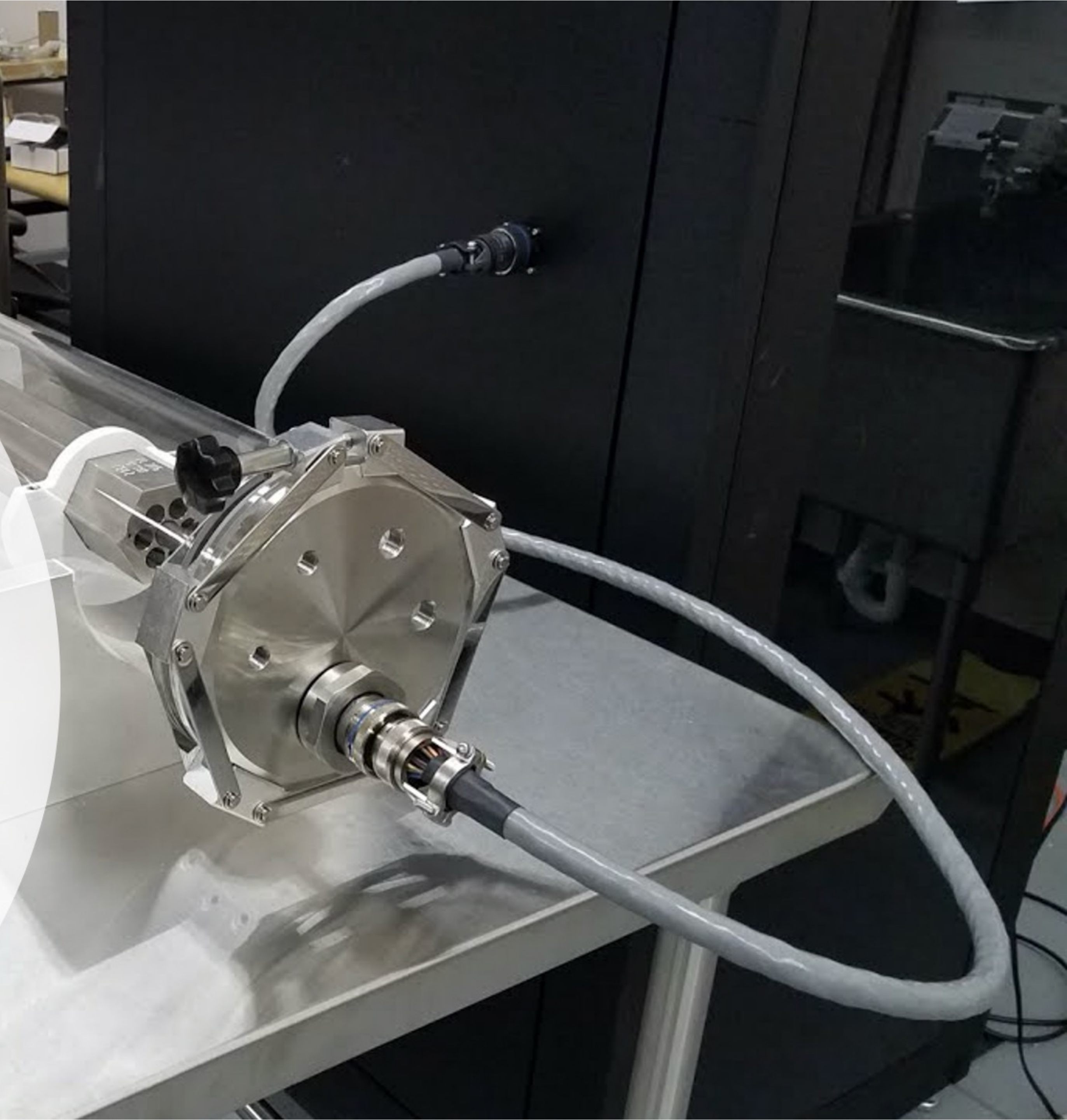
In Progress

- Gap Conductance Testing for NRC
- Working for Industrial Partner on understanding the effect of orientation on heat pipe performance
- Database Accessibility

MRP Microreactor Program

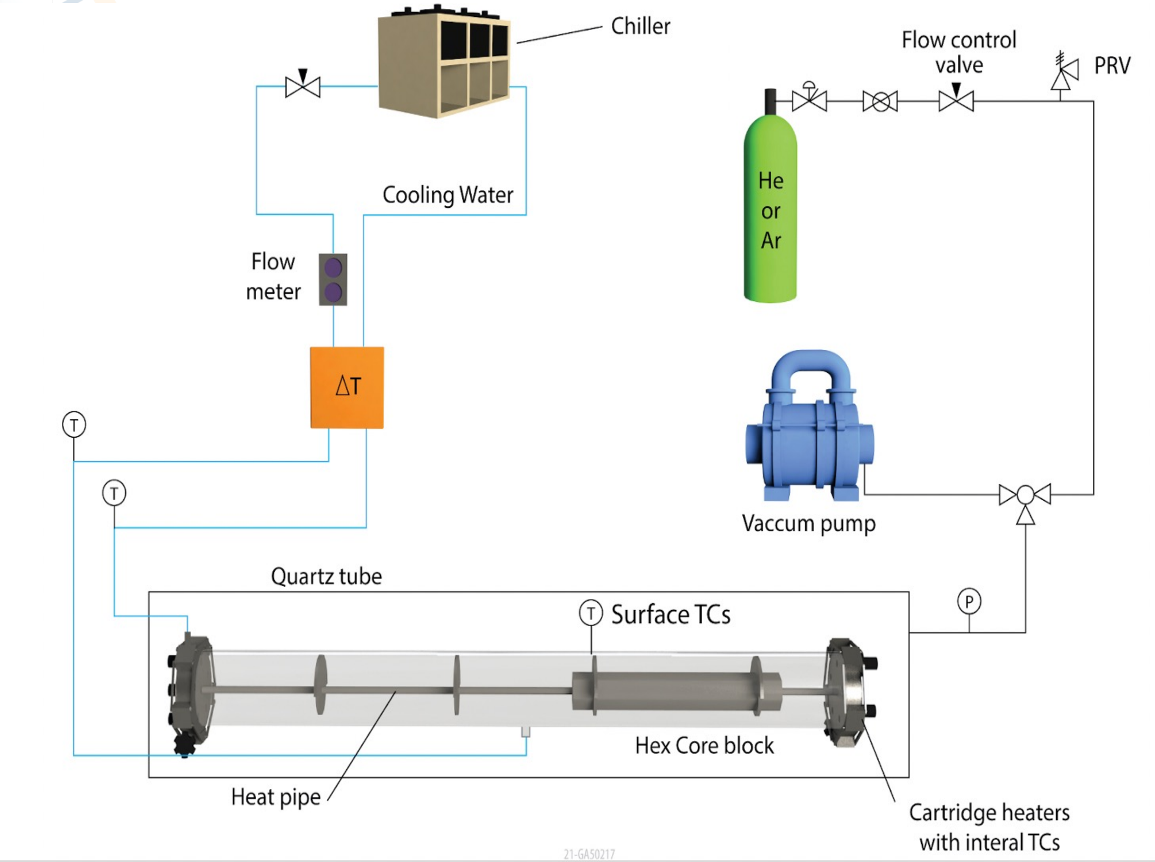
SPHERE Purpose

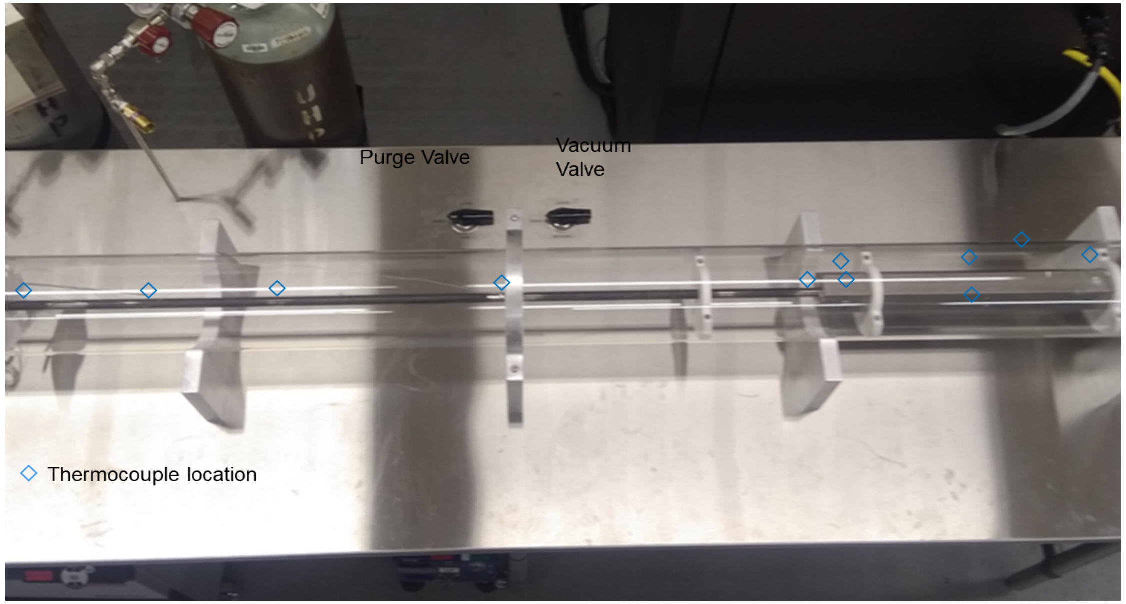
- Verification and Validation activities for microreactor programs
- Initially supporting heat pipe testing
- Preliminary testing of instrumentation and controls to be deployed in MAGNET

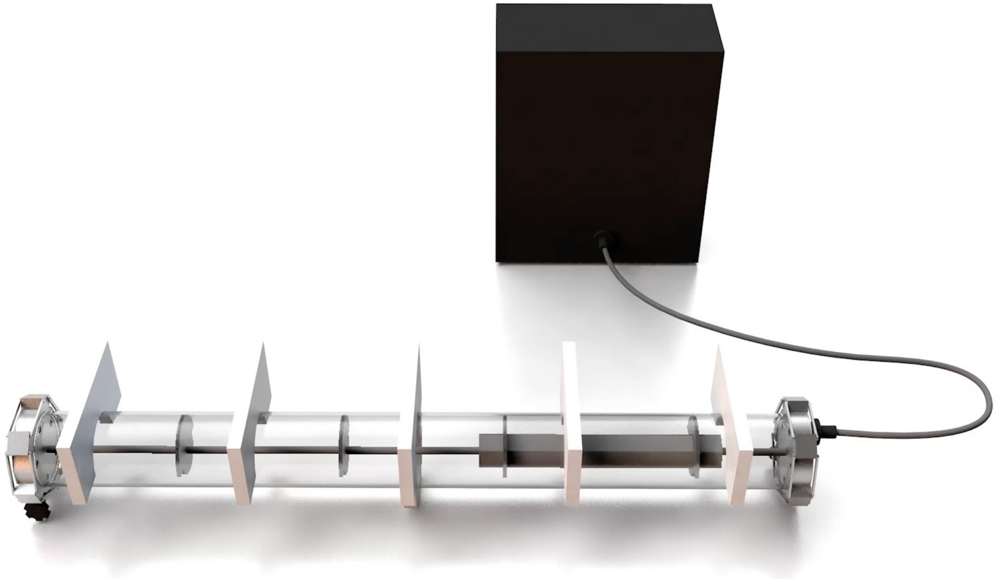


SPHERE System Design

- 6” diameter 8’ long quartz tube
- Maximum power rating of 20 kW
- Vacuum, Helium, Nitrogen, or Argon atmosphere



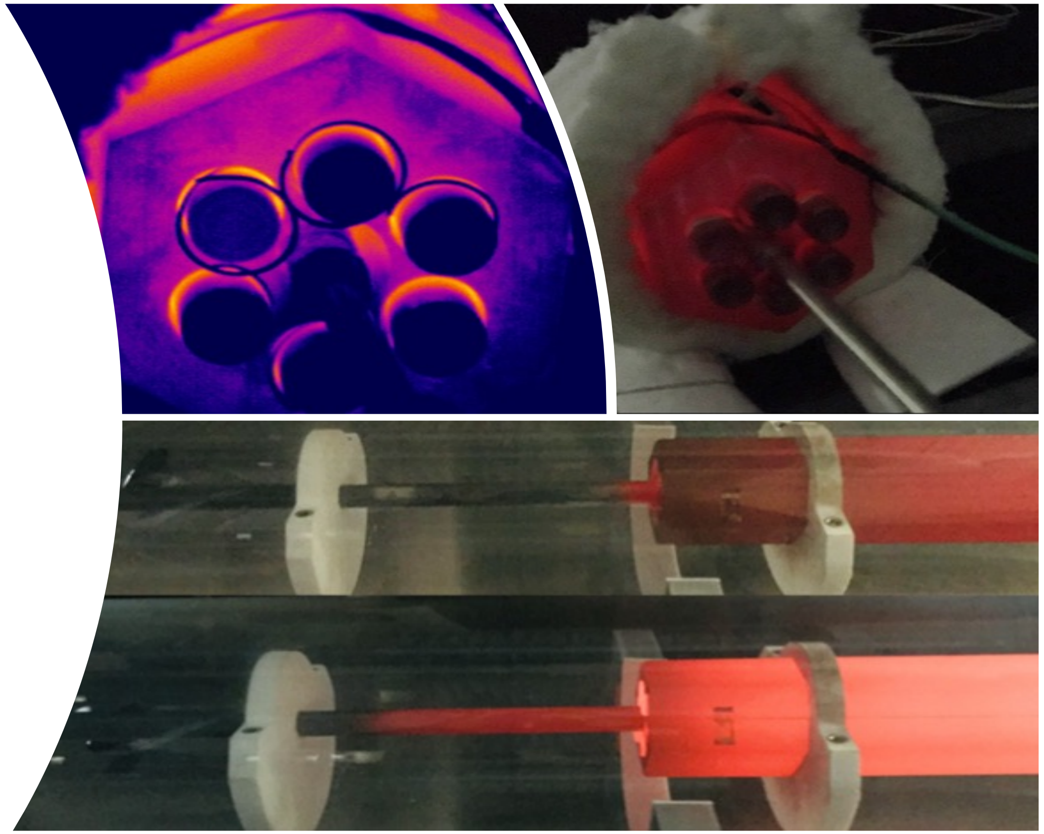




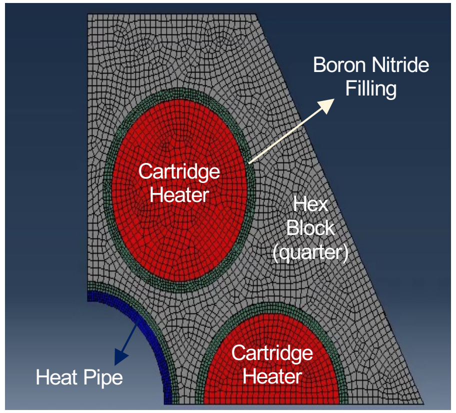
SPHERE: ACT Heat Pipe

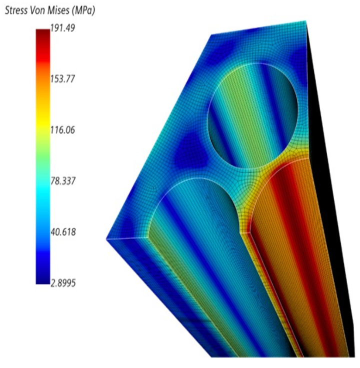
ACT Heat Pipe

- Pipe material: SS 316
- Geometry: smooth-wall tube, proprietary wick
  - Wick: sintered stainless steel
- Length: 2 m, Diameter: 0.625-in.
- Working fluid: sodium, non-condensable inert gas
- Operating temperature, ~740°C
- Heat-removal rating: 1 kW

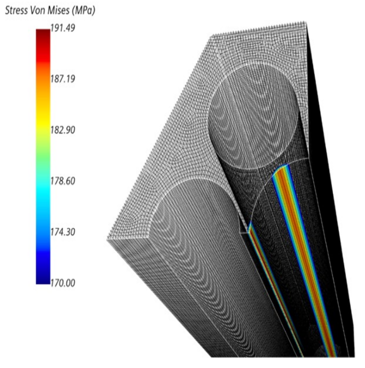


Coupled Thermal and Structural Analysis for Heat Pipe Experiments: To guide experiment testing



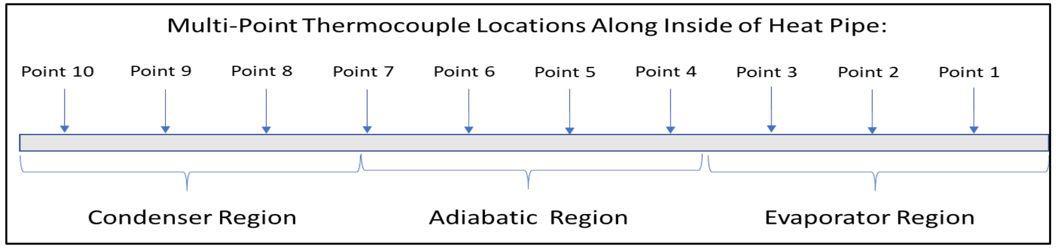


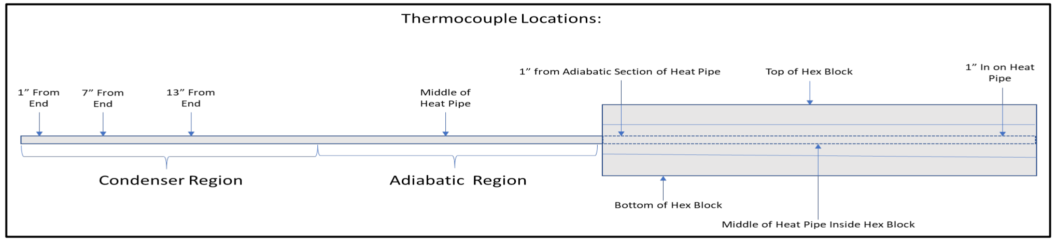
(a) Distribution of Von Mises Stress



(b) Location of Maximum Von mises Stress

Testing of Commercial Heat Pipe – Shakedown Testing





The ACT heat pipe has an internal thermowell running down the center of the heat pipe. A multi-point thermocouple is inserted into the heat pipe.

Small fine gauge wire thermocouples are attached externally to the heat pipe and hexblock, as well as inside the gap between the hexblock and the heat pipe.

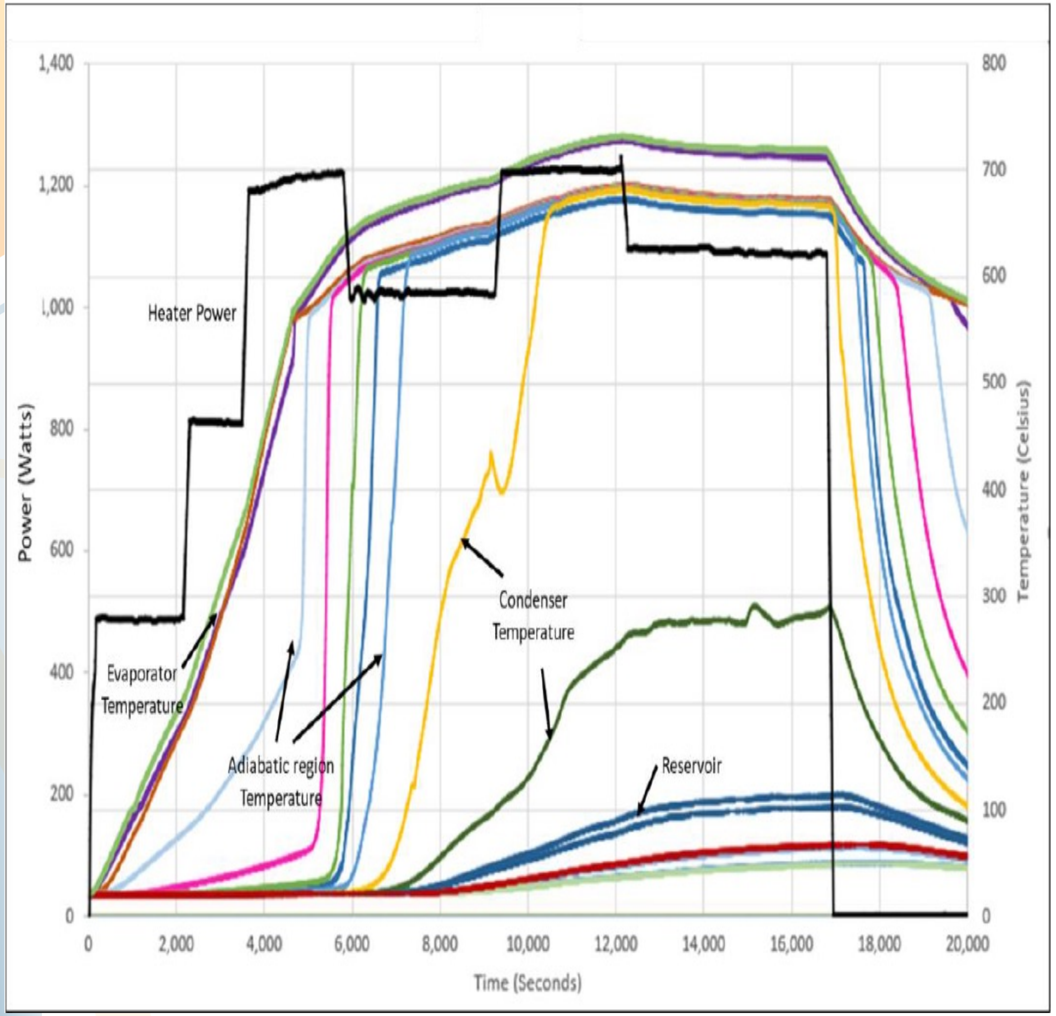
Verify instrumentation and controls

Experimental data correlates with manufacturer data

Initial data from shakedown testing being used to help with tool validation

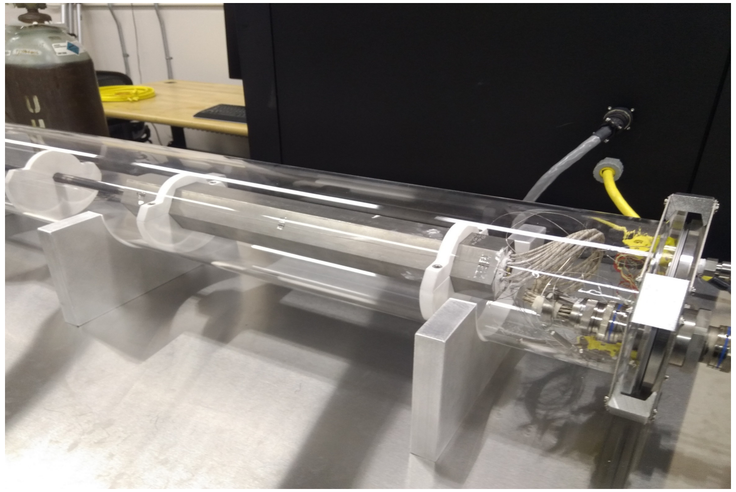
MRP Microreactor Program

Testing of Commercial Heat Pipe



Accomplishments

- Verify instrumentation and controls
- NEAMS and SOCKEYE use the data from the testing to validate and tune their models
- Experimental data correlates with manufacturer data
- Initial data from shakedown testing being used to help with tool validation



Ongoing Activities

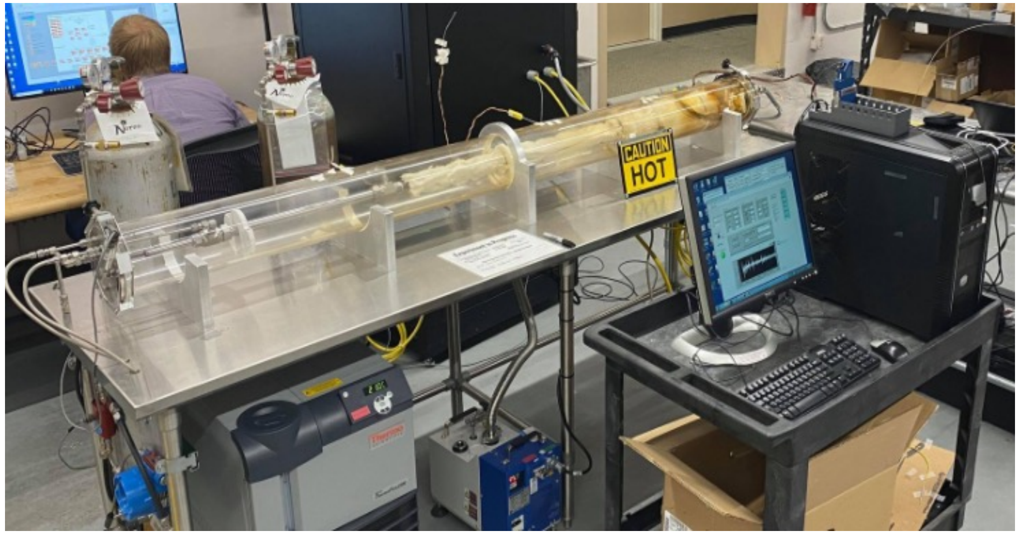
- Interlayer gap conductance testing
- Heat pipe orientation experiments

Sabharwall, P., J. Hartvigsen, T. Morton, Z. Sellers, and J. S. Yoo, *SPHERE Assembly and Operation Demonstration*, INL/EXT-20-60782, Idaho National Laboratory, December 2020.

MRP Microreactor Program

SPHERE Facility – Modifications (Ongoing)

- **Objective**
  - Obtain data on the thermal conductivity of the gap between the heat pipe and the hex block center hole with various gas compositions
- **Challenges**
  - Quartz tube was too small
    - Led to thermocouple burnout at the junctions
  - Unexpected manufacturing lead times
    - Led to using a different setup then initially designed
- **Solutions**
  - Replacing quartz tube with sanitary, clamp style tubing
  - Manufactured parts completed



Initial SPHERE gap conductance test with quartz tube

Example of sanitary tubing that is replacing quartz tube

MRP Microreactor Program

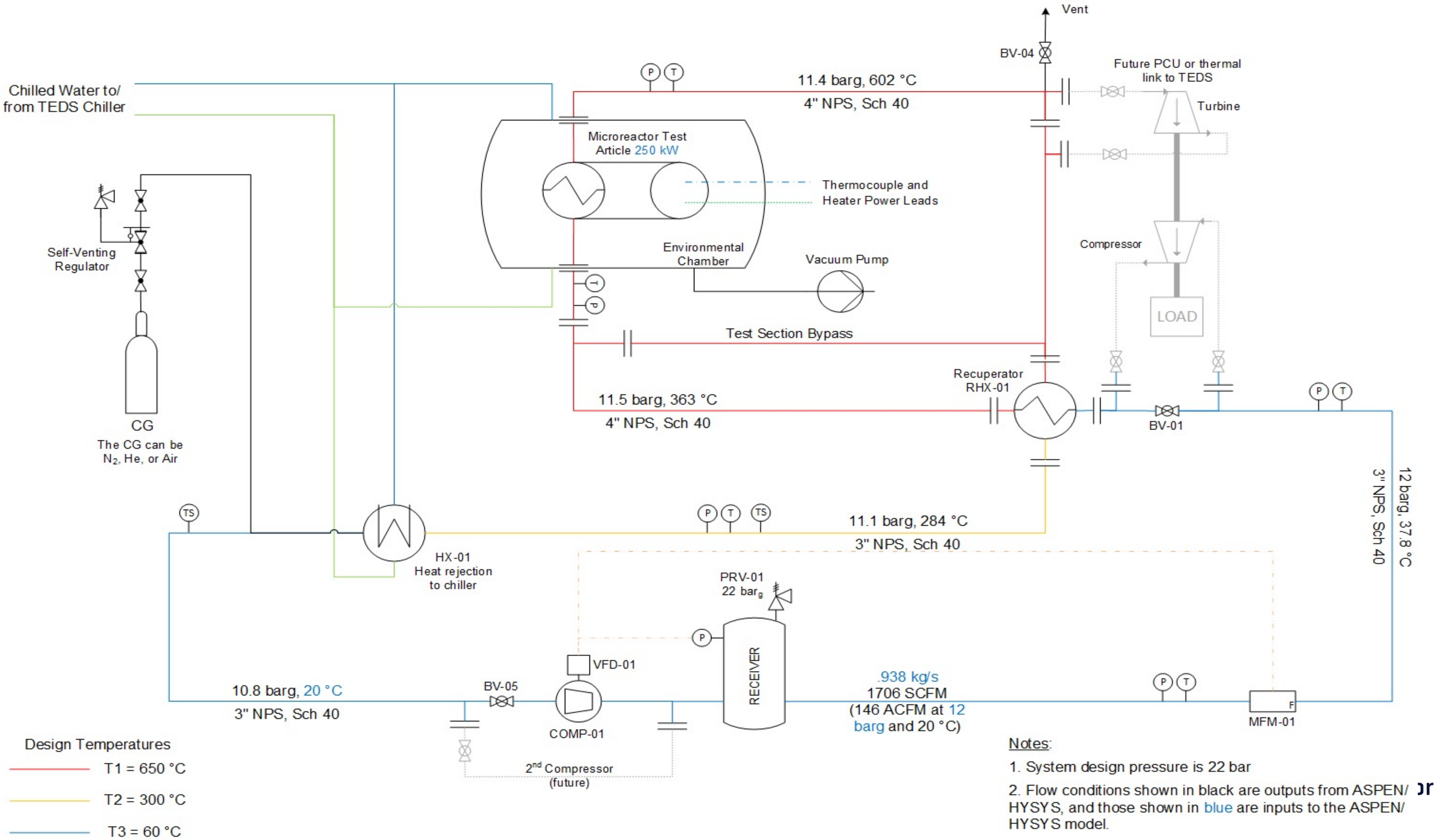
Microreactor AGile Non-nuclear Experimental Testbed (MAGNET)

- General-purpose test bed for performance evaluation of microreactor design concepts (heat pipe, gas-cooled, other).
- Provide detailed reactor core and heat removal section thermal hydraulic performance data for prototypical geometries and operating conditions.
- Demonstrate interface of heat removal section to power conversion system for power generation.
- Provides for integrated materials, instrumentation testing
- Co-located with integrated energy systems R&D capabilities

Parameter	Value
Chamber Size	5 ft x 5 ft x 10 ft
Heat Removal	Liquid-cooled chamber walls, gas flow
Connections	Flanged for gas flow and instrumentation feed through and viewing windows
Coolants	Air, inert gas (He, N2)
Gas flow rates	Up to 43.7 ACFM at 290 psig
Design pressure	22 barg
Maximum power	250 kW
Max Temperature	750 C
Heat Removal	Passive radiation or water-cooled gas gap calorimeter

MRP Microreactor Program

MAGNET Process Flow Diagram (PFD)



Notes:

1. System design pressure is 22 bar
2. Flow conditions shown in black are outputs from ASPEN/ HYSYS, and those shown in blue are inputs to the ASPEN/ HYSYS model.

FY-22 Plans

Single Primary Heat Extraction and Removal Emulator (SPHERE)

- **M3** – Complete Fabrication and procurement of test article, perform test for gap conductance testing and report on findings (March 30th 2022)
- **M4 –** Provide NEAMS tool developers experimental data under different gas compositions and power levels (April 30th 2022)
- **M3 –** Provide NEAMS tool developers experimental operating curve for heat pipe to support validation effort for Sockeye (August 30th 2022)

Microreactor Agile Nonnuclear Experiment Testbed (MAGNET)

- **M3** - Complete Single Heat pipe Test Campaign (Feb 24th 2022)
- **M2** - Installation of 75 kW (37 Heat Pipe) Test Article in MAGNET (Sept 22nd 2022)

MRP Microreactor Program

Single Primary Heat Extraction and Removal Emulator (SPHERE)

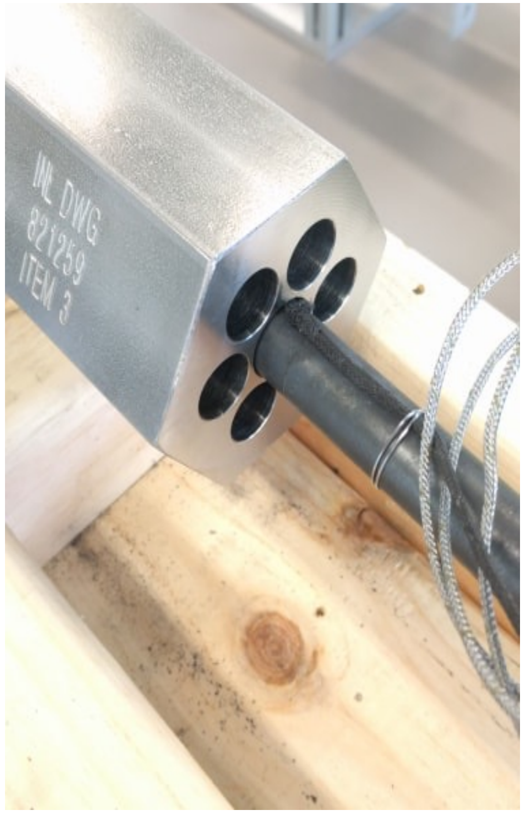
Jeremy Hartvigsen, PhD | Research Engineer

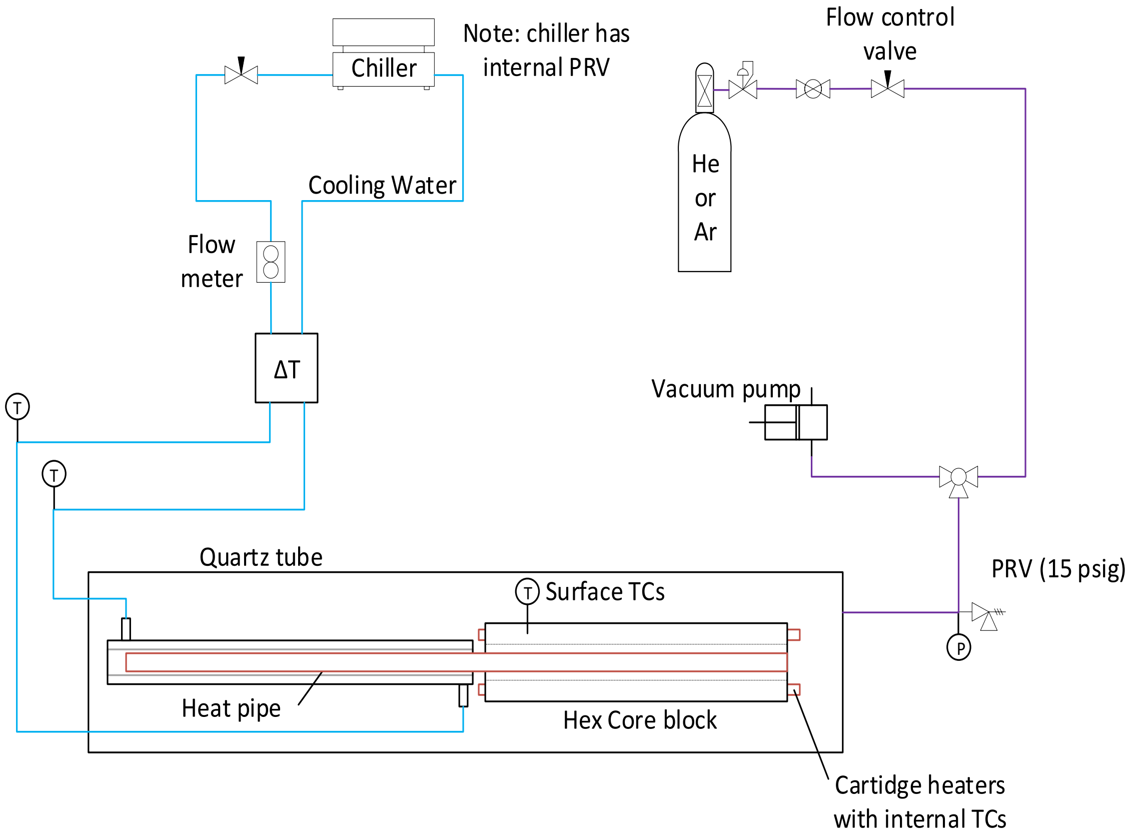
SPHERE Purpose

- Validation and Verification activities for microreactor programs
- Initially supporting heat pipe testing
- Preliminary testing of instrumentation and controls to be deployed in MAGNET

SPHERE—Primary Measurements

- Power In
- Heat Out
- Temperature
- Gas Environment
  - Pressure
  - Oxygen Content
- Strain Gauges

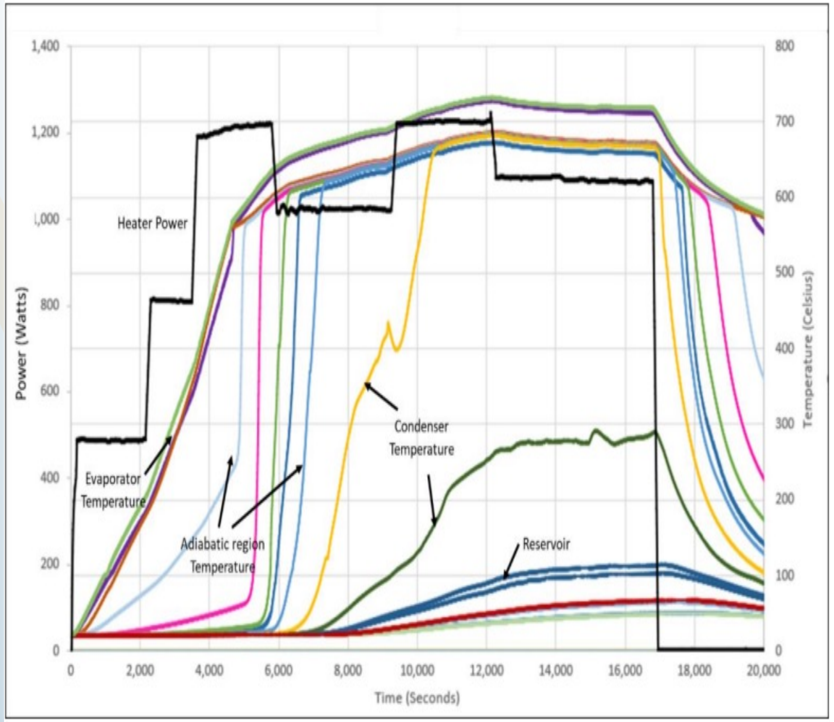


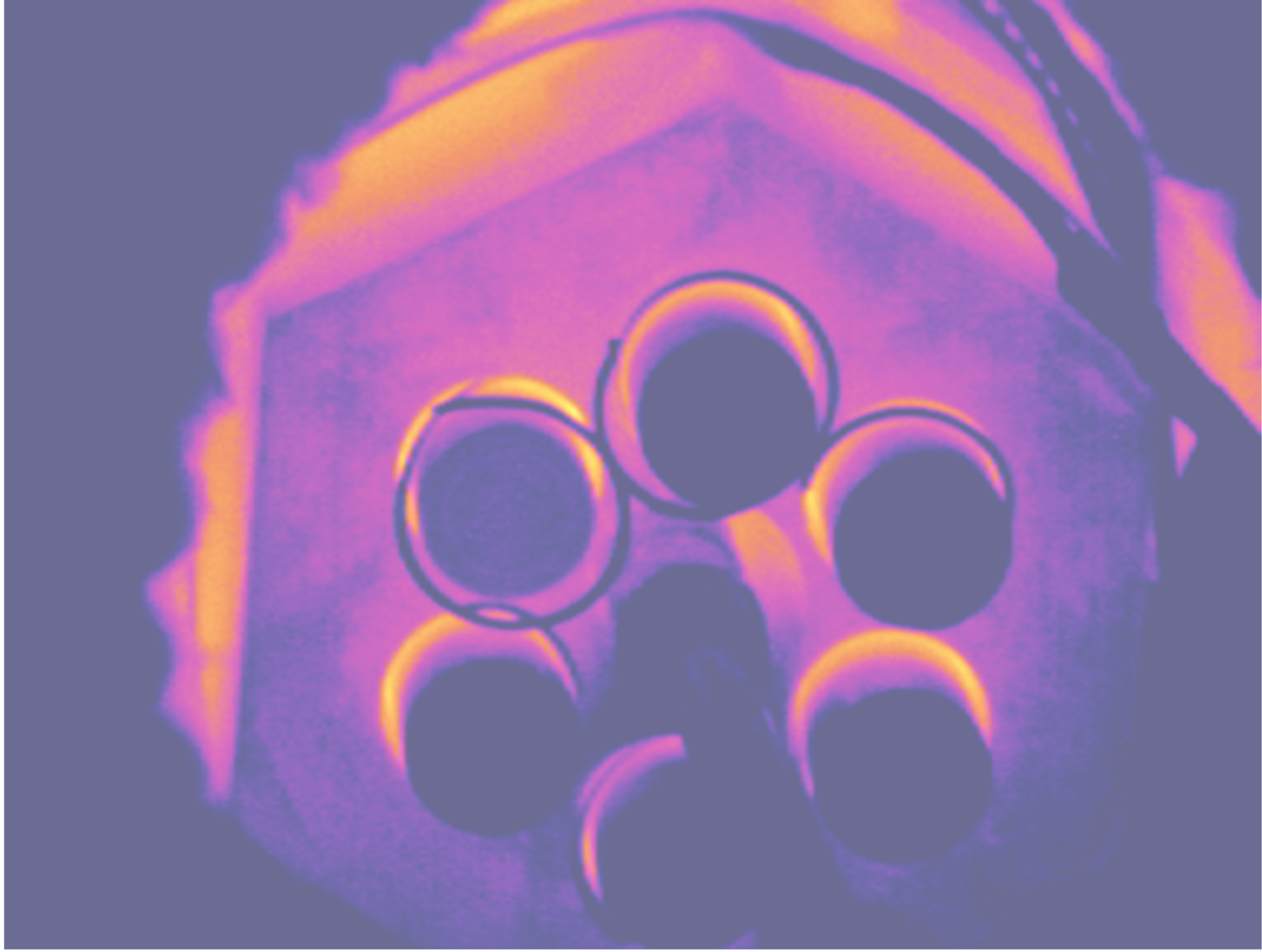


MRP Microreactor Program

Outline

- Rebuilt System
  - New Testbed
- Lessons Learned
  - Gap Conductance
- Ongoing and Future work



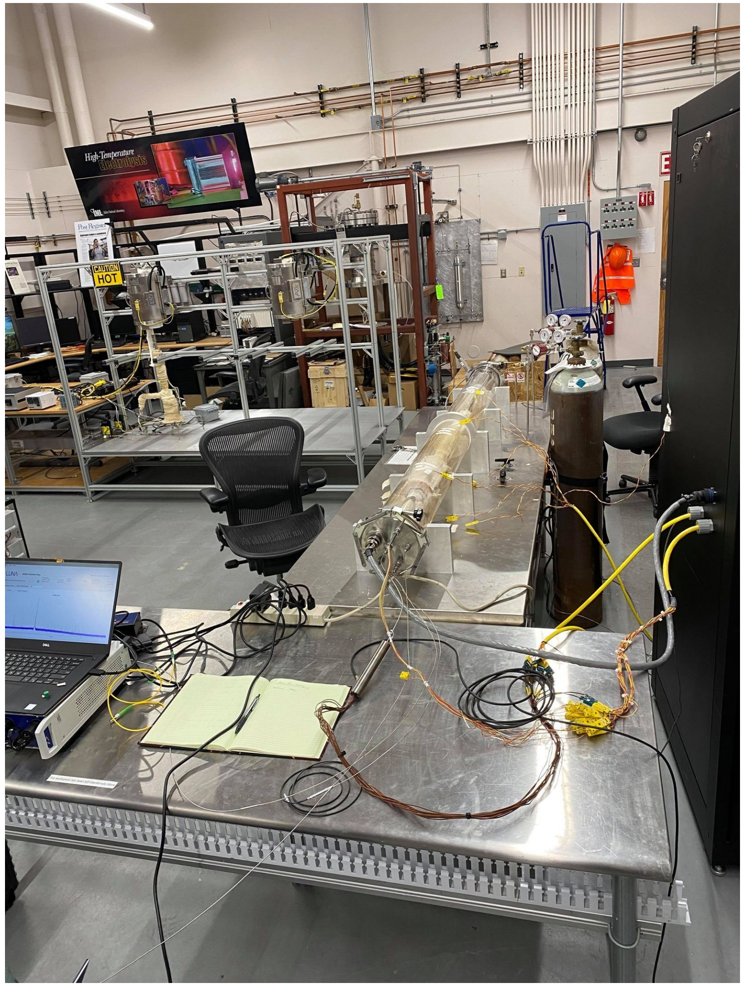


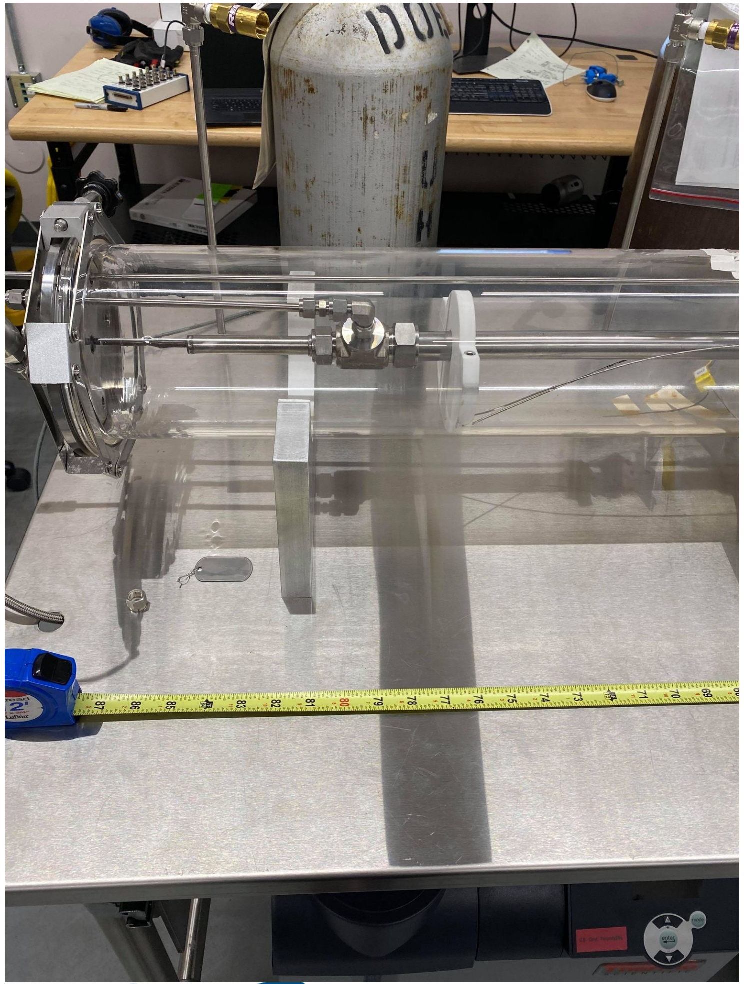
MRP Microreactor Program


Updated Test Fixture

Lessons Learned

- Challenges encountered with quartz tube
  - Difficult assembly procedure
  - Length
  - Heat loss

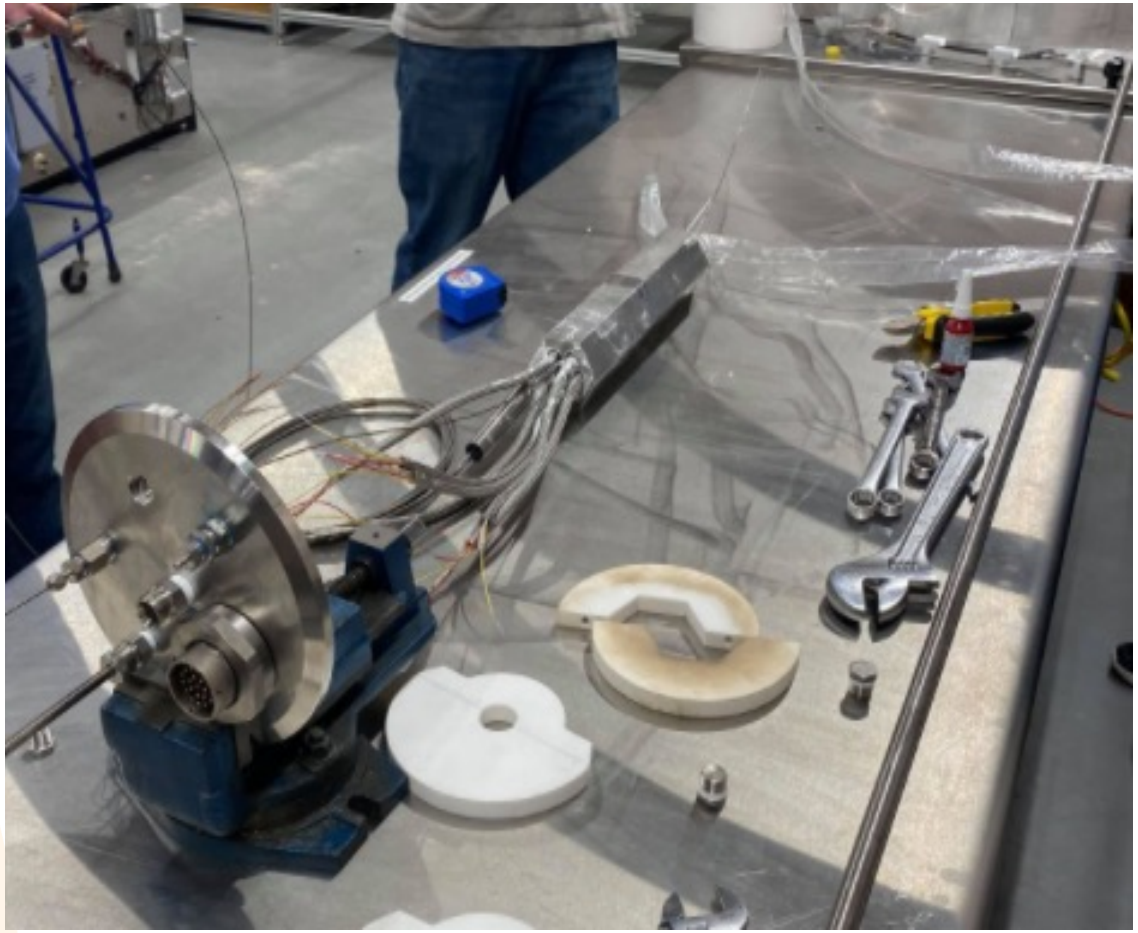


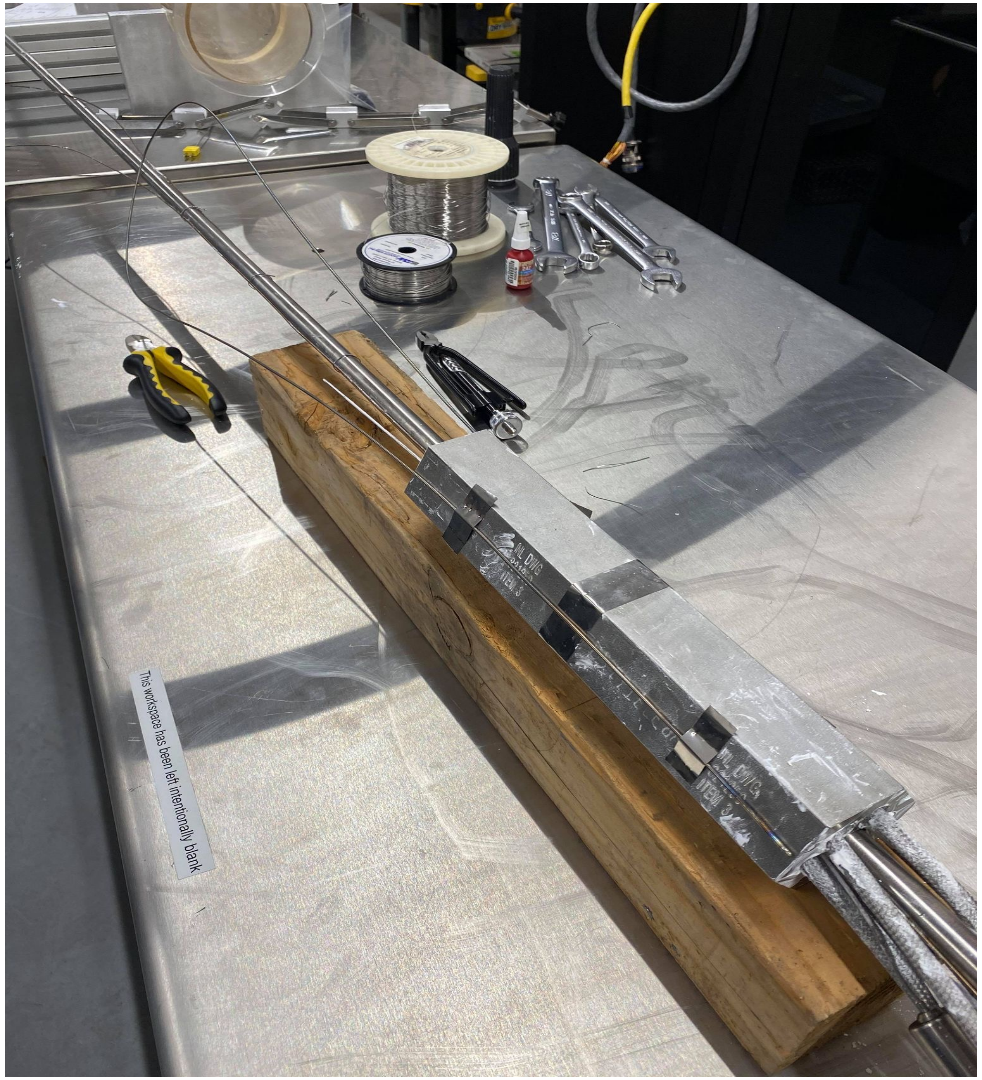


MRP Microreactor Program

Lessons Learned

- Fiberoptic sensor issues
  - First sensor broke
- Ultrasonic sensor data collection

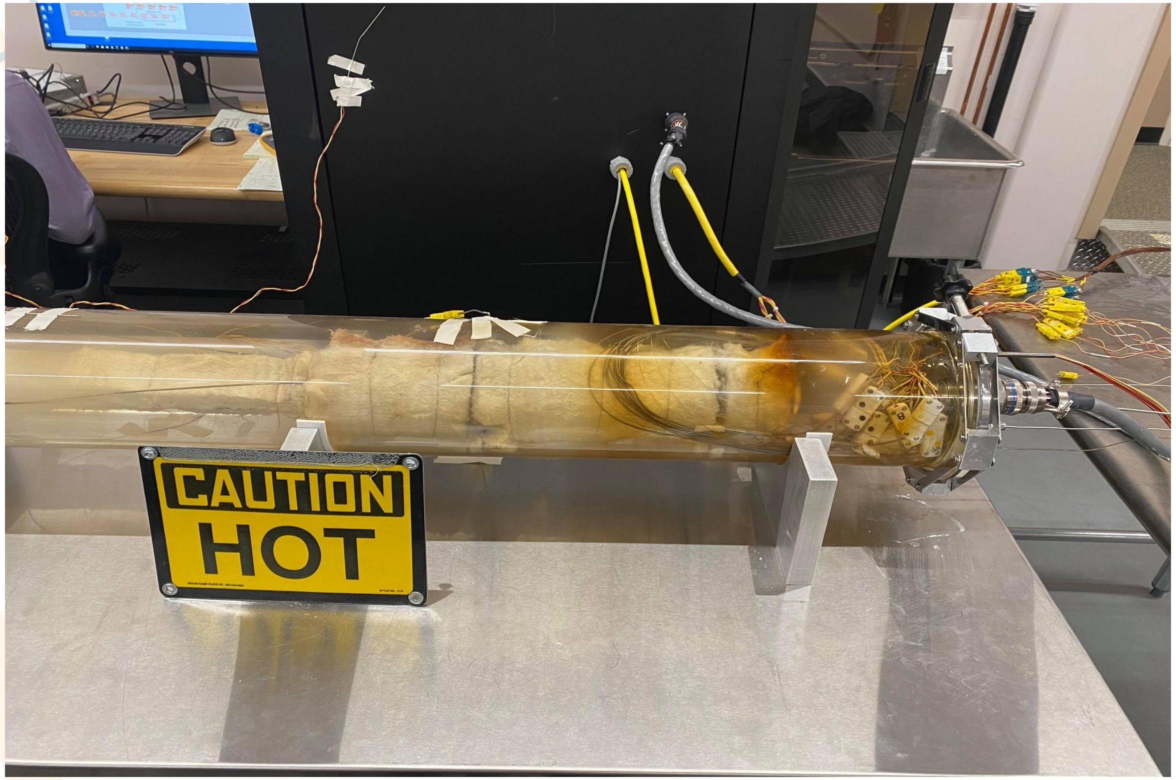


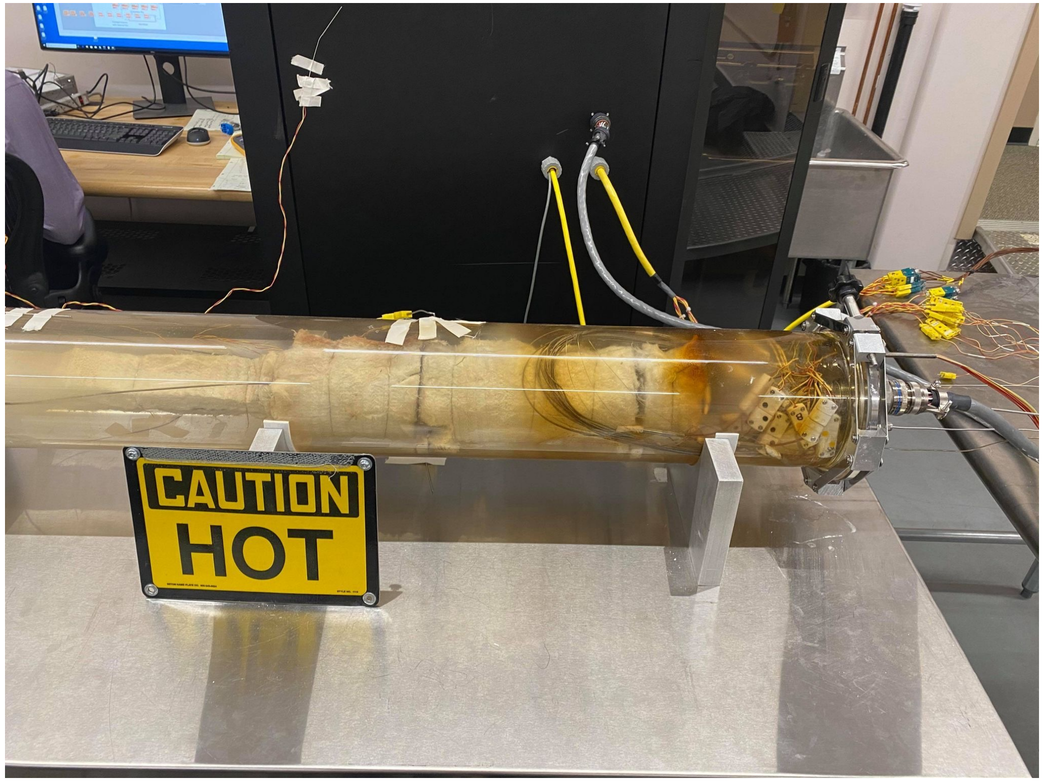


MRP Microreactor Program

Lessons Learned

- Thermocouple junction burnouts





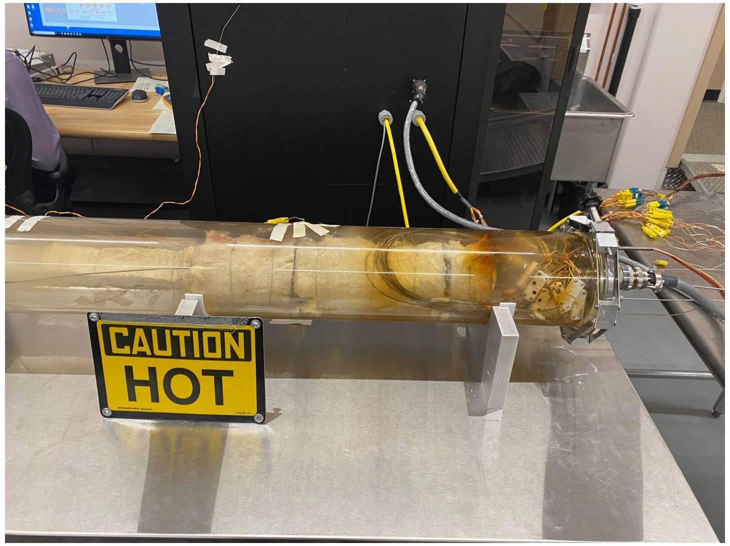
MRP Microreactor Program

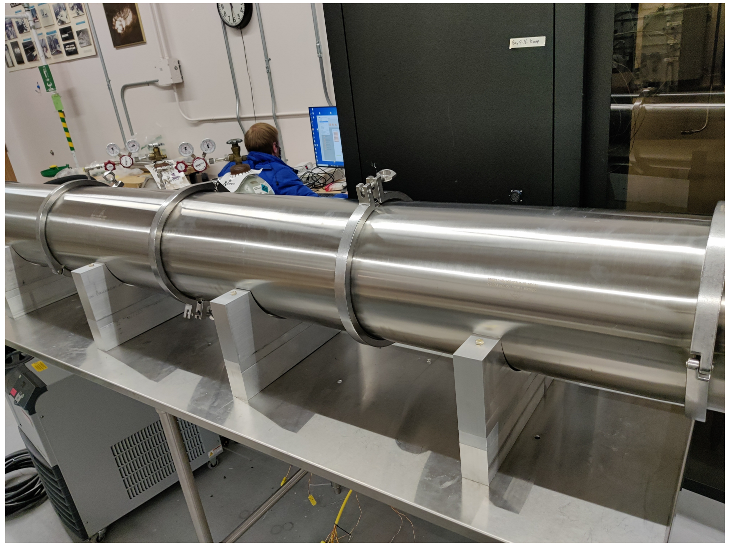
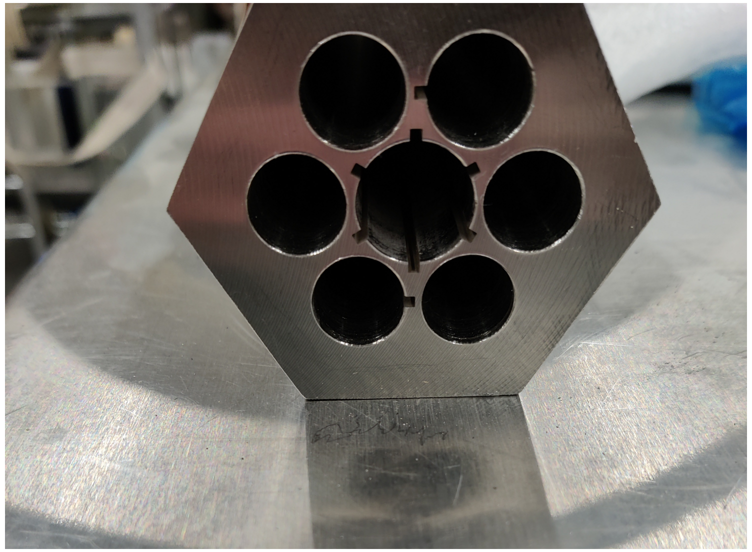
Root Causes

1. Testbed chamber is inadequate for accessibility and assembly
2. TC routing too tight
3. Secondary test article creates additional complexity
4. Contact resistances are significant source of model error

Rebuilt SPHERE Test Stand

- 12 inch diameter sanitary tubing replaced the quartz tube
- Full length wire EDM machined hex block has been completed
- Installed fiber optic and ultrasonic sensor to fit within the machined hex block
- Extra multipoint thermocouple redundancies.
- Integral junction thermocouples on the exterior

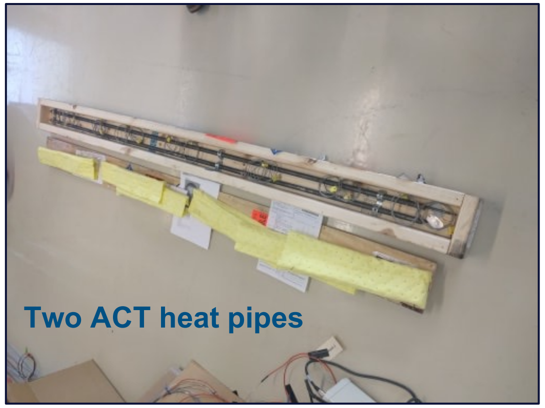


MRP Microreactor Program

Internal heat pipe temperature measurements for sensor demonstration

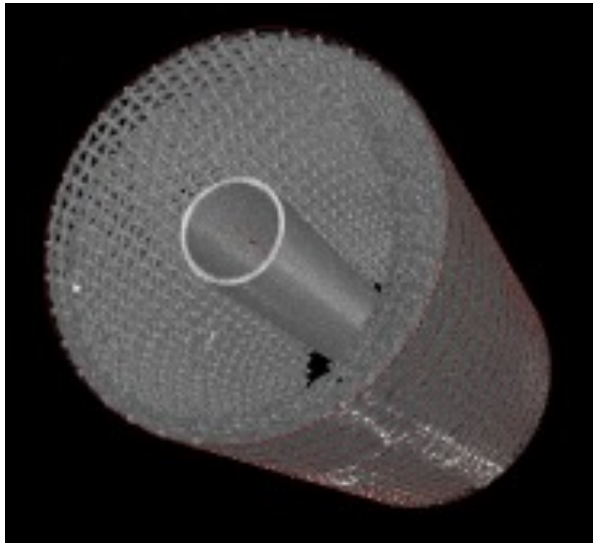
- <u>Two</u> commercial 78.75” long 0.625” OD sodium-filled heat pipes available
  - Include 78.5” long, 0.125” ID thermowell for instrument and sensor demonstration



Two ACT heat pipes

Thermowell (0.125” ID) in sodium filled heat pipe (0.625” OD) for distributed temperature sensor deployment

Specialized 3-D system with 1” through ports for long specimens

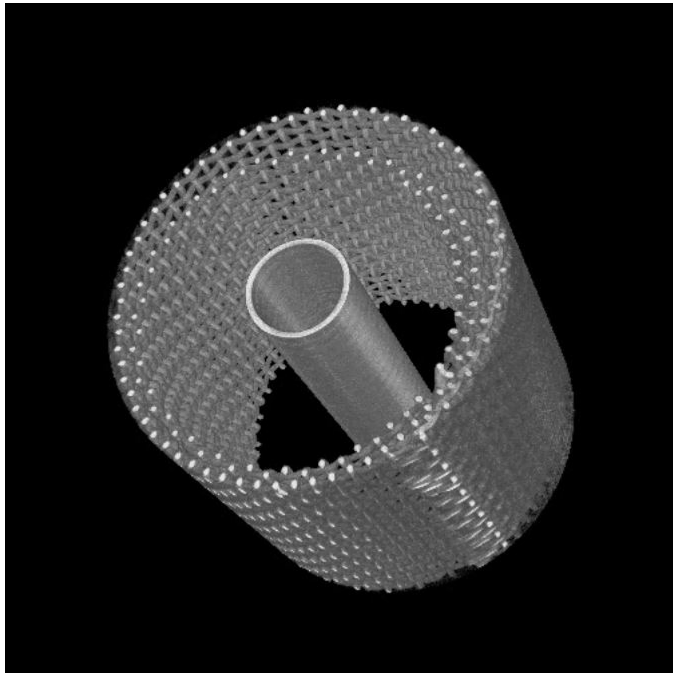


3D CT scan of sodium filled heat pipes with (above) thermowells for instrument testing

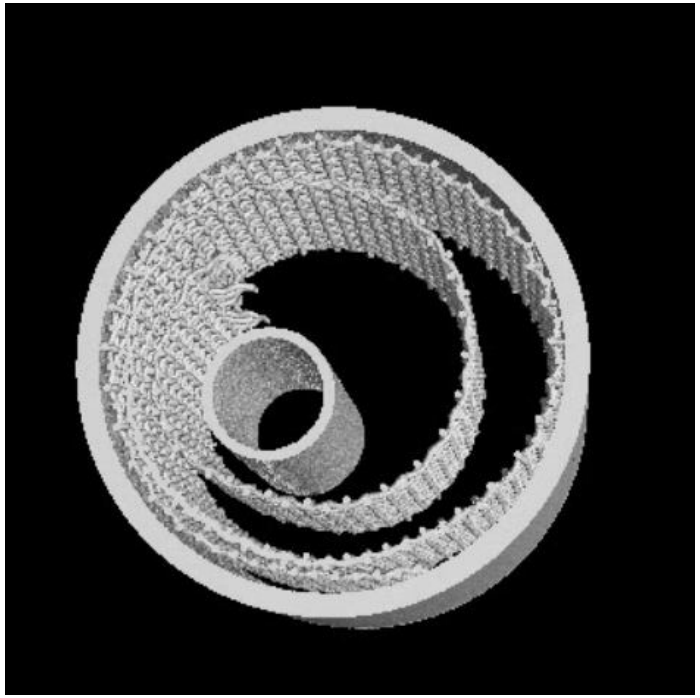
MRP Microreactor Program

3-D CT scan of ACT heat pipe before/after heating

- Can confirm radiographs were NOT taken at the same location



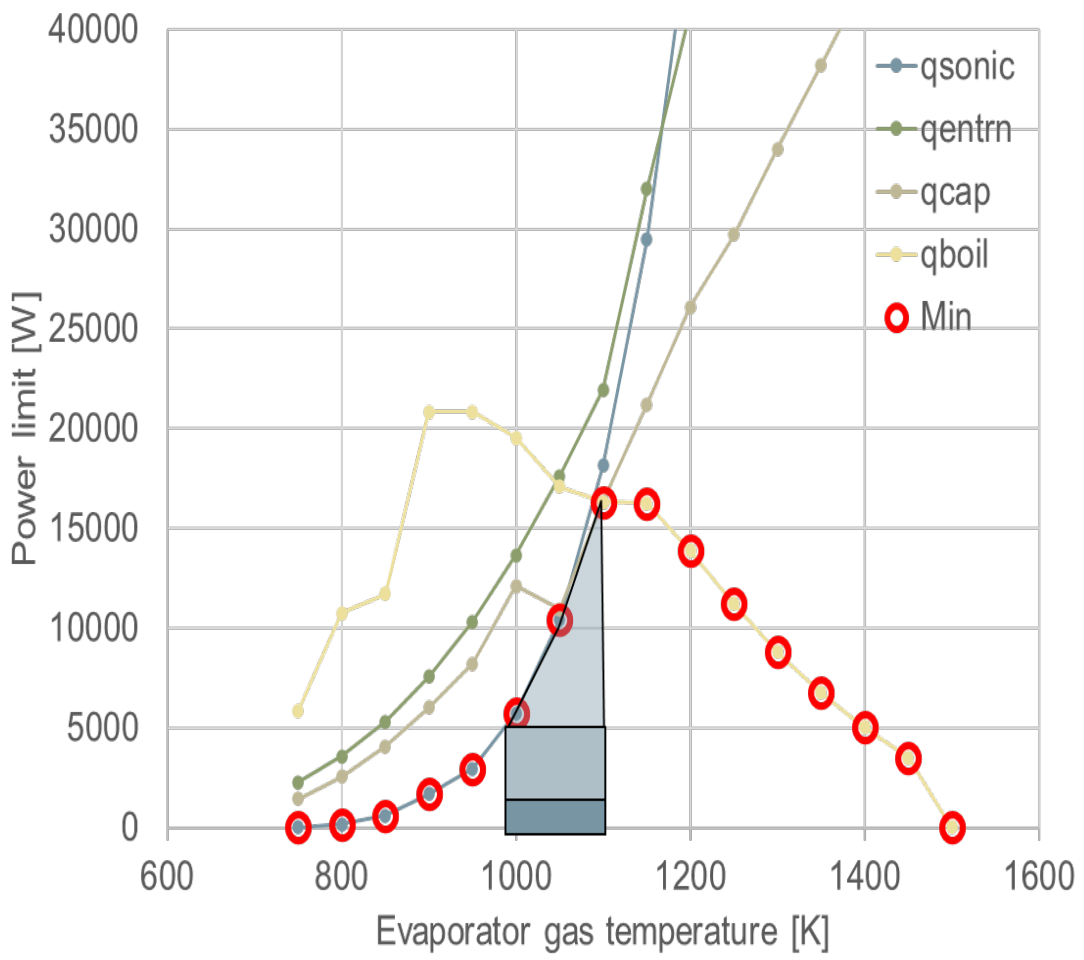
Before heating (central location)



After heating (worst location)

SPHERE Activities—External Vendor

- Evaluation of heat pipe performance for external microreactor vendor
  - Lower Power Testing
    - Vertical performance tests
  - Heat pipe limit testing
    - High power temperature control loop
  - Compare vertical and horizontal performance
    - Low Power
    - High Power



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Ongoing and Future SPHERE Work

- Run embedded sensor test article
  - ORNL
- Gap-conductance test
- LANL heat pipe
- Run 15kW test article once the induction heater arrives
  - Continue testing external vendor heat pipe
- Support NEAMS tools

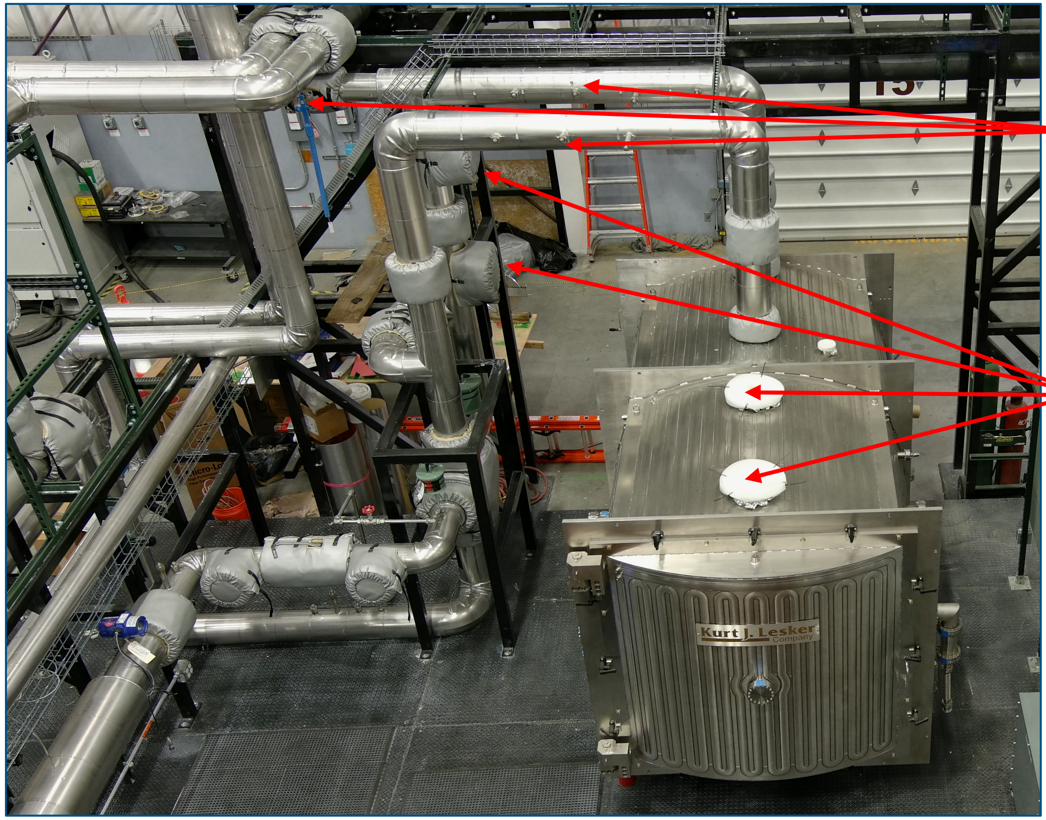
MRP Microreactor Program

Microreactor AGile Nonnuclear Experiment Testbed(MAGNET)

TJ Morton | Research Engineer

MAGNET Status

- Finishing preparations to run single heat pipe testing in March
- Construction in progress for helium component testing facility (He-CTF) addition to MAGNET



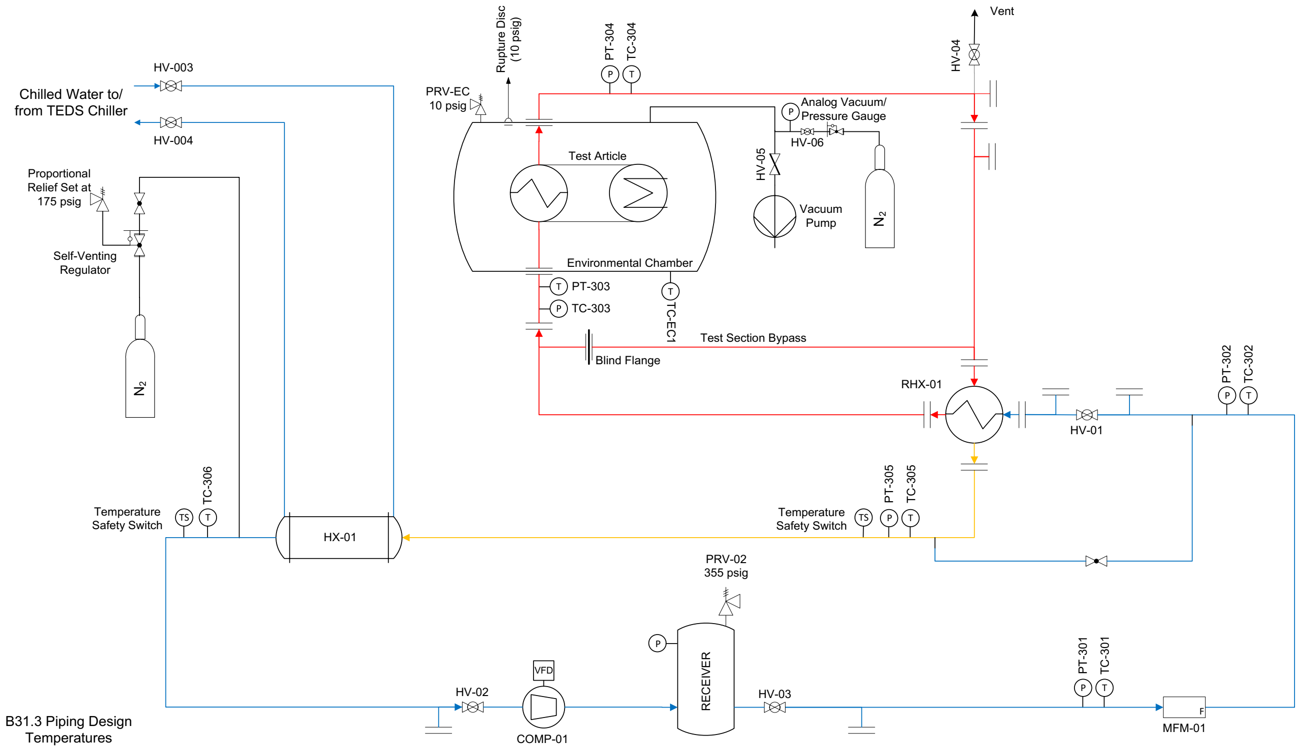
Installing scaffolding for safe staff access to I&C and vent valve

Connection points for He-CTF

MRP Microreactor Program

MAGNET Single Heat Pipe Testing

- Awaiting final review and acceptance of Laboratory Instruction (work control for experiments at INL)
- Incorporating review comments for test plan
- Completed process hazard analysis with relevant SMEs
- Technicians finishing installation of instrumentation
- Finishing LabView Virtual Instrument programming



Single Heat Pipe Test Process and Instrumentation Diagram (P&ID)

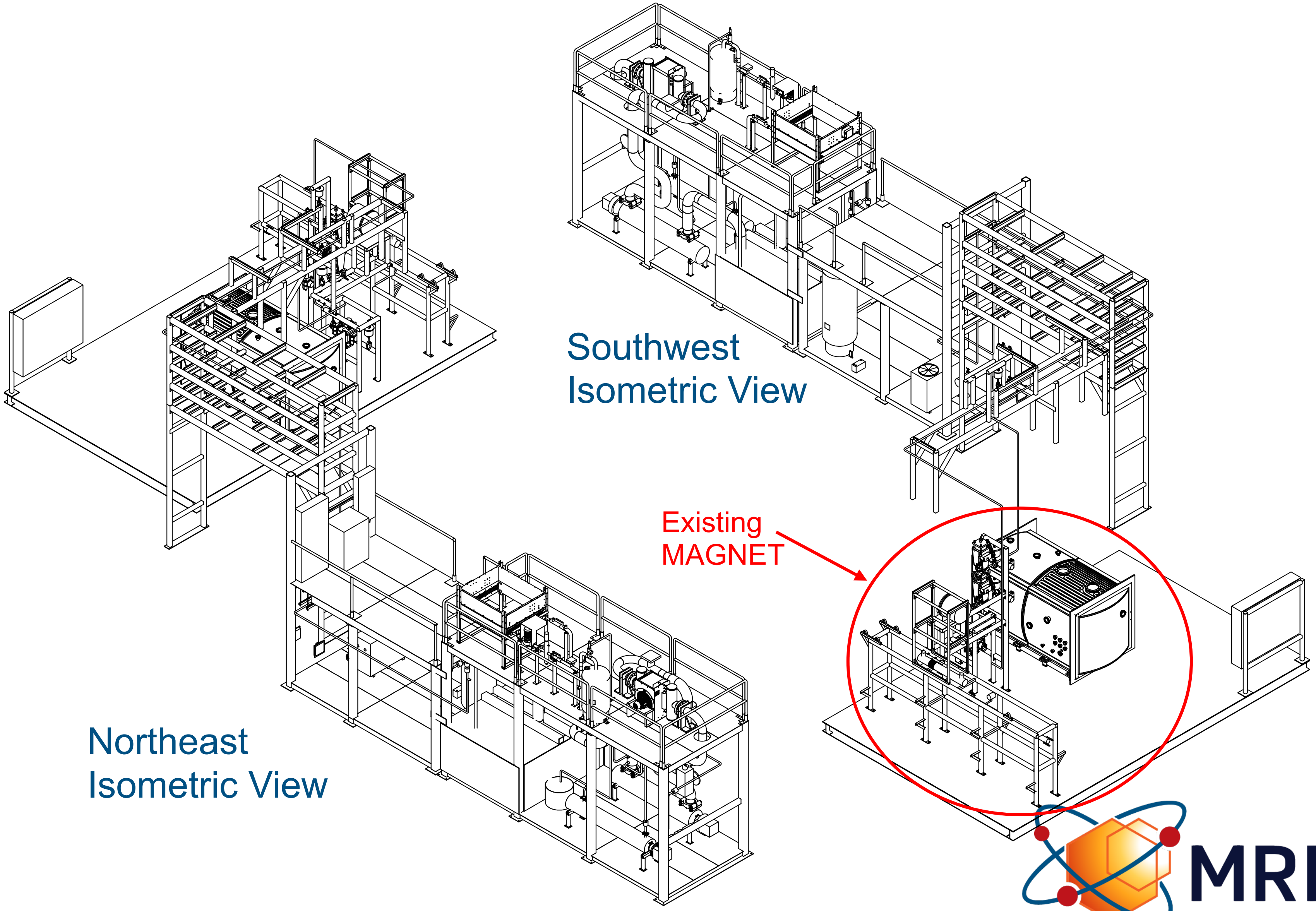
MRP Microreactor Program

MAGNET Plans

- Complete single heat pipe testing – March 18
- Complete phase I construction for He-CTF – mid-April
- External manufacturer testing in support of SCO microreactor program (two test articles) – April to May
- Complete phase II construction for He-CTF – July 30
- External manufacturer testing in support of SCO microreactor program (one test article) – August to September
- Potential testing for Radiant Nuclear – September to November
- Installation and testing of 75 kW, 37 heat pipe test article from LANL – December to March 2023

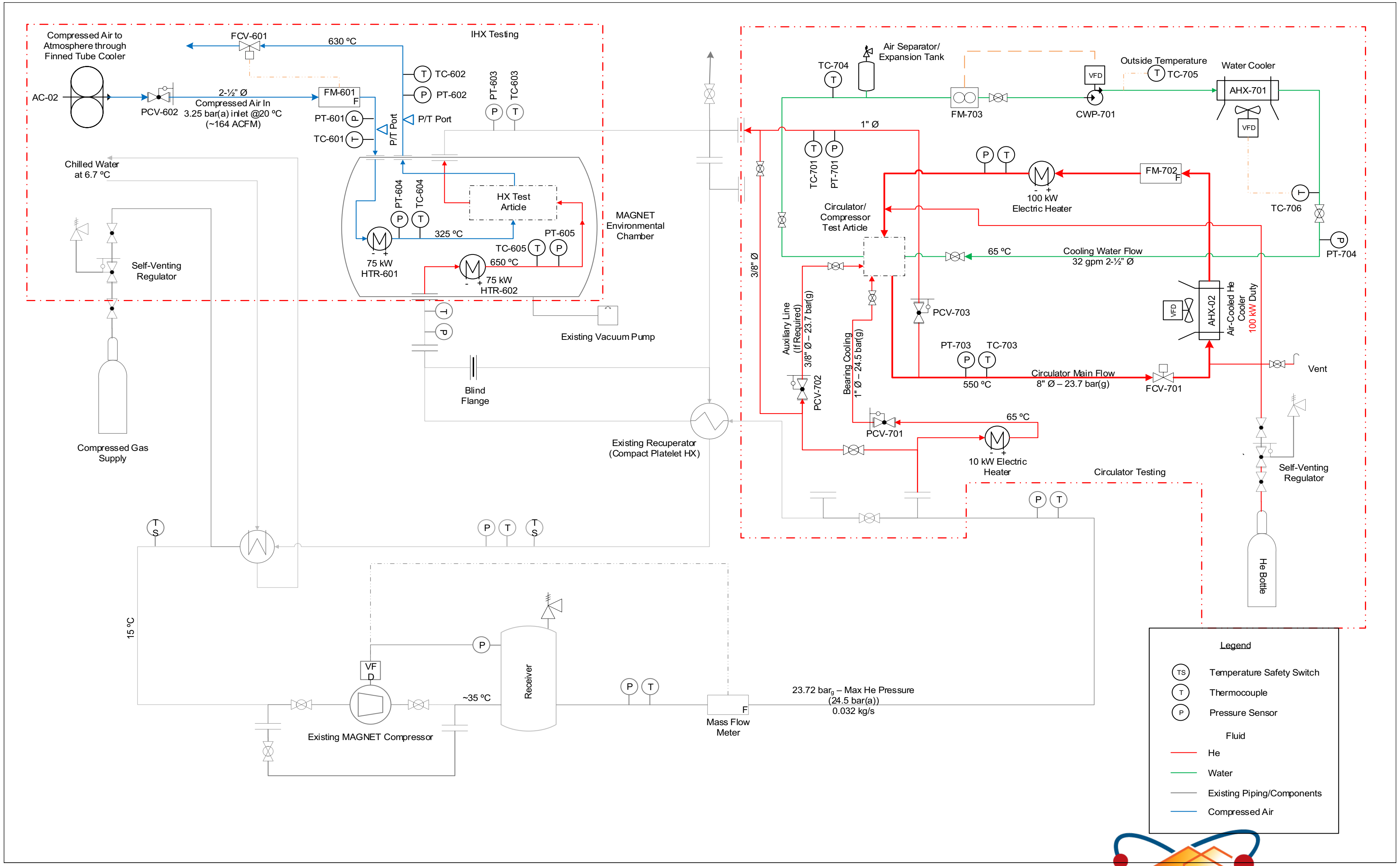
MRP Microreactor Program

Helium Component Test Facility (He-CTF)



Microreactor Program

He-CTF Flow Diagram



MRP Microreactor Program

He-CTF Overview

HX Testing

- Helium design conditions
  - 325°C in
  - 650°C hot supply
  - 20 bar_g
  - 0.07 kg/s
- Preheated compressed air design conditions
  - 350°C in
  - 630°C out
  - 150 psig
  - 0.212 kg/s

Circulator Testing

- Helium design conditions
  - 550°C
  - 24 barg
  - 1.5 kg/s
- Circulator cooling water(50% BV ethylene glycol) design conditions
  - 200°F
  - 100 psig
  - 32 gpm
  - Air cooled

MRP Microreactor Program

He-CTF Status

- He-CTF construction funded by National Reactor Innovation Center (NRIC)
- Construction in progress for HX testing portion with expected completion mid- to late April
- Testing for SCO microreactor program HX late April to May
- Construction drawings complete, addendum to phase I contract issued with expected completion mid-July
- Testing for SCO microreactor program circulator August to September

MRP Microreactor Program

NEUP Program

Experiments for Modeling and Validation of Liquid-Metal Heat Pipe Simulation Tools for Micro-Reactors

March 04, 2022

Yassin. A. Hassan | Texas A&M University

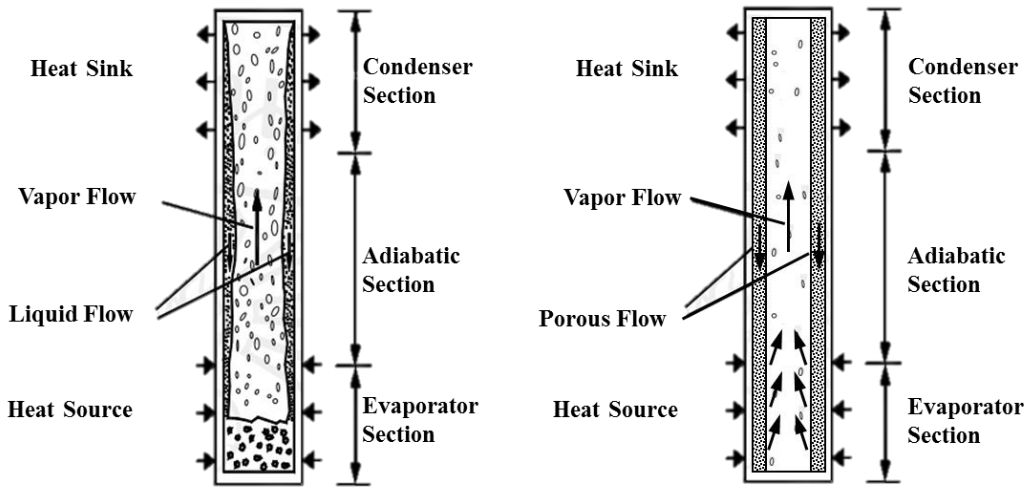
Joseph Seo | Texas A&M University

Daeguen Kim | Texas A&M University

Hansol Kim | Texas A&M University

Rodolfo Vaghetto | Texas A&M University

Overview of the Project



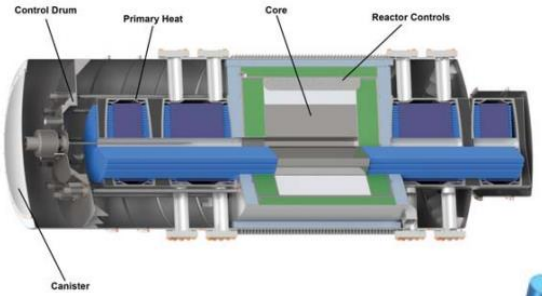
- The heat pipe is a device of very high conductance
- It works passively on the principle of evaporation and condensation of a working fluid so that it can transfer large amount of heat.
- Intensive studies to apply the heat pipe as a primary heat transfer system of the micro-reactor have been pursued.

Spacecraft

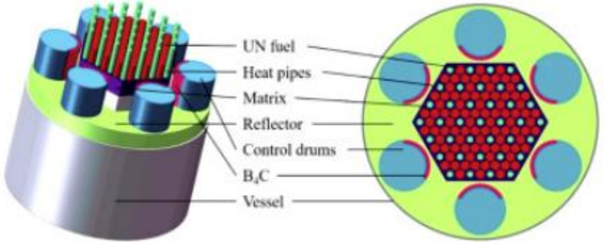
Computer

Pipeline

Spacecraft, heat pipes in computer, Alaska pipeline support legs cooled by heat pipe thermosyphons to keep permafrost frozen.
From: Heat pipe – Wikipedia and wall.alphacoders.com



Design of e-Vinci from Westinghouse



Wang et al., Thermal-hydraulic analysis of a new conceptual heat pipe cooled small nuclear reactor system (2018)

Single heat pipe test in MAGNET experimental station in INL.

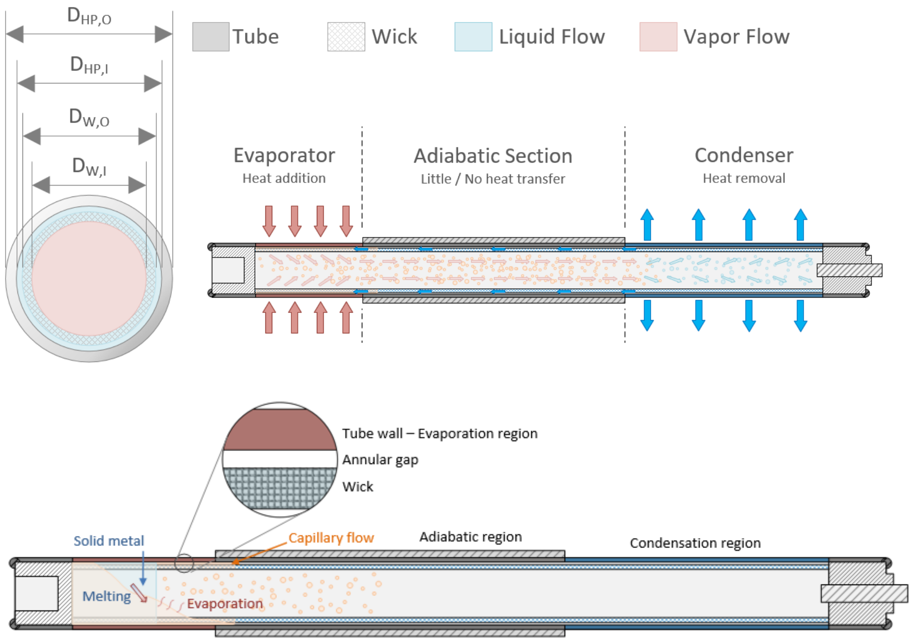
MRP Microreactor Program

Overview of the Project

<u>Purpose</u>: The proposed work aims to produce high-fidelity liquid-metal heat-pipe experimental data for the validation of the simulation tool, Sockeye, through both single heat-pipe and integrated heat-pipe experiments.

<u>Objectives:</u>

- **Single Heat-Pipe Hydraulic Experiment**
  Measurements of the hydraulic resistance for validation / development of wall friction, wick friction/form loss models.
- **Single Liquid-Metal Heat-Pipe Experiment**
  Measurements of internal temperature, pressure, and phase distribution for validation/development of heat transfer and flow models in Sockeye.
- **Multiple Liquid-Metal Heat-Pipes Experiment in Hexagonal Arrangement**
  Investigate the integrated system performance under various operational scenarios such as partial failure of constituent heat pipes and non-uniform cooling/heating.



Sodium heat pipe with targeted design

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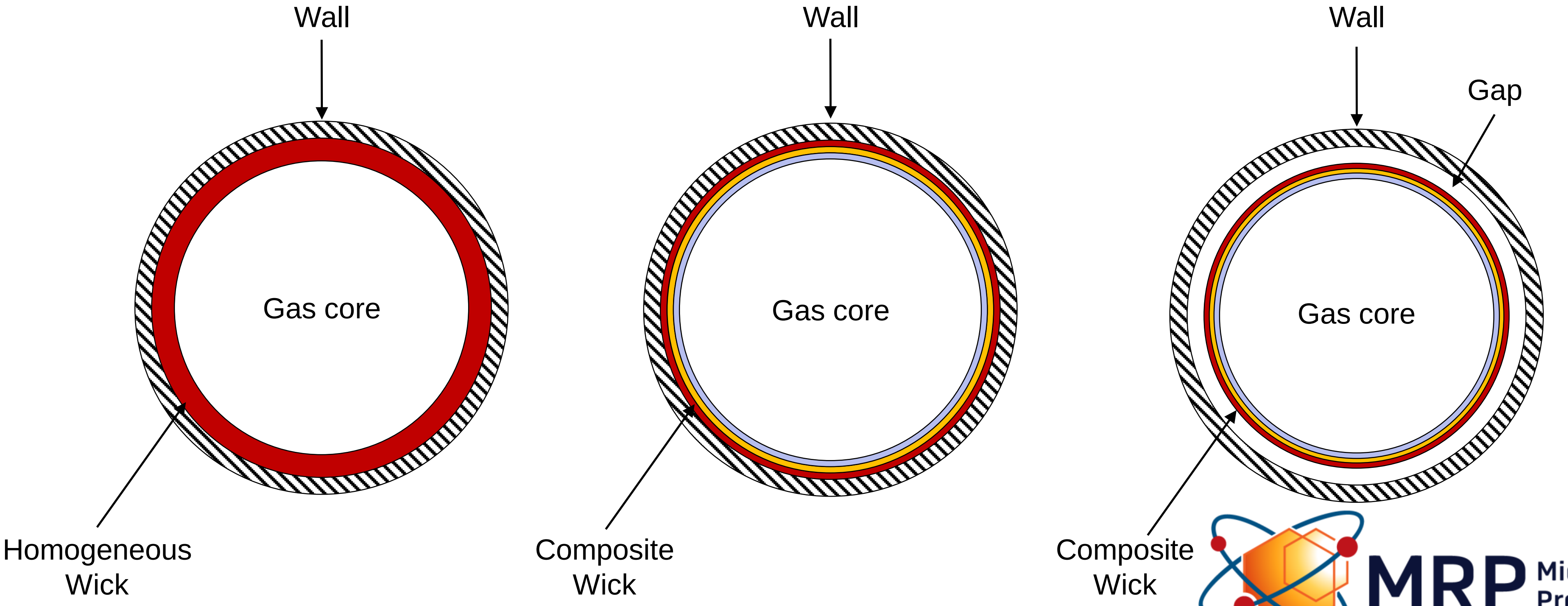
Experiments at TAMU

- **Wick Characteristics Experiment**
- Gap Effect Experiment
- Capillary Rising Modeling
- Heat Pipe Fabrication and Experiment
- Heat Pipe Measurement
- Heat Pipe Visualization

MRP Microreactor Program

Introduction

- Pore radius, or pore size, is an average size of voids inside the porous media. This parameter should be small to acquire a large capillary pressure difference between the evaporator and condenser region.
- For a heat pipe, the permeability is a parameter of the wick resistance to the liquid flow along the pipe axial direction. Large permeability is needed for achieving a small liquid pressure drop along the wick structure.
- Having a low pore radius and a high permeability is hard to achieve in most homogeneous wick designs (Optimization/Tradeoff problem).
- The composite wick structures provide high capillary pressure by having small pores, while gaining high permeability from large size pores.
- The other way to overcome the tradeoff problem is to introduce an extra flow path for liquids other than wick structures.



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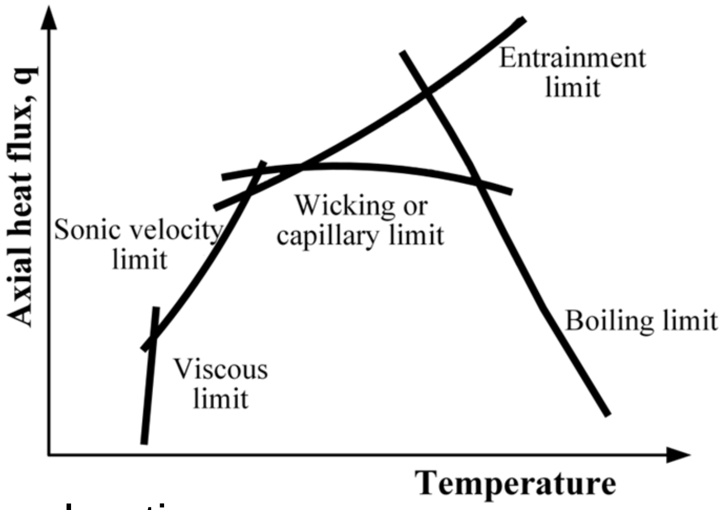
Operating Limitation of the Interest

Capillary limitation

During heat pipe operation, the working fluid evaporates in the evaporator and condenses in the condenser, transporting the latent heat from one end of the heat pipe to the other.
The liquid condensate is passively returned to the evaporator by capillary forces in the wick.
The maximum power that the heat pipe can transport and still return the condensate by capillary forces is the capillary limit.



$$\Delta P_c > \Delta P_g + \Delta P_v + \Delta P_l$$

ΔP_c: Capillary force generated in the wick

ΔP_g: Pressure drop due to gravitation and acceleration

ΔP_l: Liquid pressure drop in the wick

ΔP_v: Fractional pressure drop in the vapor

MRP Microreactor Program

Operating Limitation of the Interest

Capillary limitation

ΔP_c: Capillary force generated in the wick

$$\Delta P_C = \frac{2\sigma}{r_{eff}}$$

ΔP_g: Pressure drop due to gravitational acceleration

$$\Delta P_g = (\rho_l - \rho_v) gh$$

ΔP_l: Liquid pressure drop in the wick (Darcy's law)

$$\Delta P_l = \frac{\dot{m}\mu L}{\rho_l K A_{wick}} = \frac{q}{h_{lv}} \frac{\mu L}{\rho_l K A_{wick}}$$

K: Permeability

A_{wick} : Wick cross-sectional area

ΔP_v: Fractional pressure drop in the vapor

$$\Delta P_v = \frac{f \rho_v u_v^2 L}{D_v}$$

f : Fanning friction factor

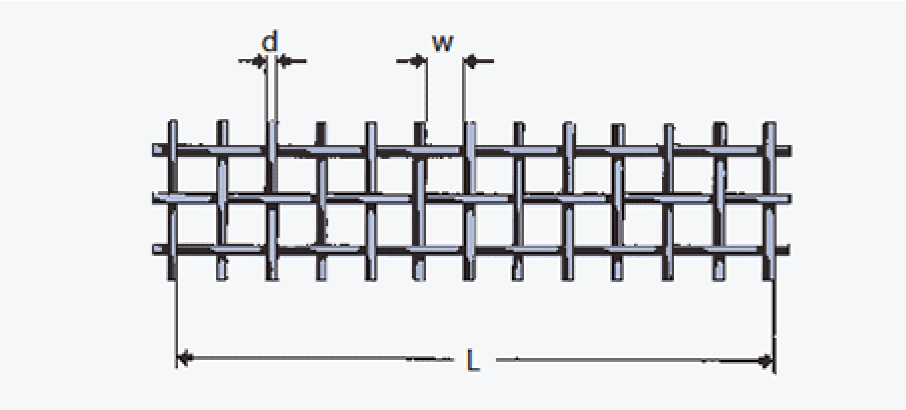
$$\Delta P_C > (\rho_l - \rho_v) gh + \frac{q}{h_{lv}} \frac{\mu L}{\rho_l K A_{wick}} + \frac{f \rho_v u_v L}{D_v}$$

$$q_C < \frac{h_{lv} \rho_l K A_{wick}}{\mu L} \left[(\rho_l - \rho_v) gh + + \frac{f \rho_v u_v L}{D_v} - \Delta P_C \right]$$

MRP Microreactor Program

Wick characteristics – Single Layer

Metal screen mesh wicks



Wick type	Wire diameter, d [mm]	Opening size, W [mm]	Opening area	r_{eff} $[mm]$ (W+d)/2	Mesh number, N=1/(W+d)	Porosity φ[-]	Permeability K[m^2]
60 x 60	0.1905	0.1397	12%	0.1651	3.028468	0.524	1.89E-10
100 x 100	0.1143	0.1524	30%	0.13335	3.749531	0.647	2.32E-10
200 x 200	0.04064	0.08636	46%	0.0635	7.874016	0.736	7.76E-11
200 x 200	0.05334	0.07366	34%	0.0635	7.874016	0.654	5.44E-11
400 x 400	0.0254	0.0381	38%	0.03175	15.74803	0.670	1.46E-11
500 x 500	0.02032	0.03048	36%	0.0254	19.68504	0.670	9.38E-12

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Test Matrix

The wick combining coarse and fine wick have superior performance since heat pipe performance requires high capillary pressure, and yet still offer low resistance to fluid flow*

Case	Type	Pore radius, d (um)	Porosity, ε	Permeability, K (m2)	Capillary Pressure (Pa)	Maximum Heat input (W)
1	100-mesh (6 wraps)					
2	400-mesh (6 wraps)					
3	60-mesh (6 wraps)					
4	100-mesh (2 wraps), 400-mesh (2 wraps), 60-mesh (2 wraps)					
5	100-mesh (1 wraps), 400-mesh (3 wraps), 60-mesh (2 wraps)					
6	100-mesh (2 wraps), 400-mesh (3 wraps), 60-mesh (1 wraps)					
7	100-mesh (2 wraps), 400-mesh (1 wraps), 60-mesh (3 wraps)					
8	100-mesh (3 wraps), 400-mesh (2 wraps), 60-mesh (1 wraps)					
9	100-mesh (3 wraps), 400-mesh (1 wraps), 60-mesh (2 wraps)					

Measured by EXP.

Calculated from theoretical models

- Mwaba et al., “Influence of wick characteristics on heat pipe performance”, 2006, Carleton University

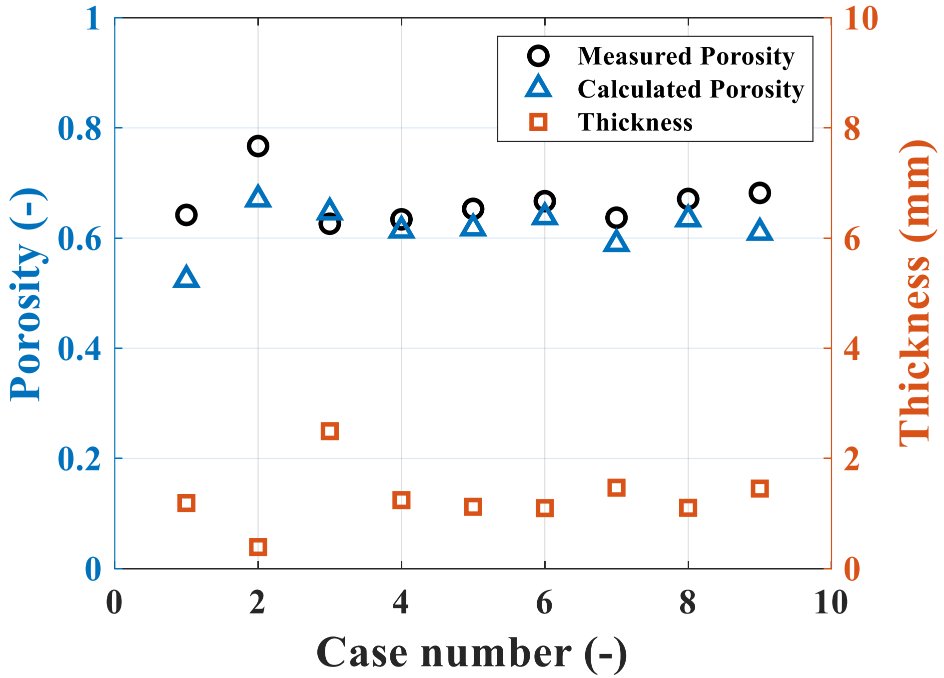
MRP Microreactor Program

Porosity Measurement

m_{wick}

$m_{wick} + m_l$

Porosity of the mesh: $\frac{1}{\varepsilon} = 1 + \frac{m_{wick}\rho_l}{m_l\rho_{wick}}$



Wick Characteristics Experiment

Porosity measurement

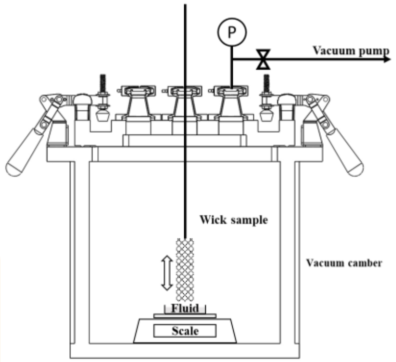
Porosity is calculated from the mass and density of the liquid filling void space of the mesh.

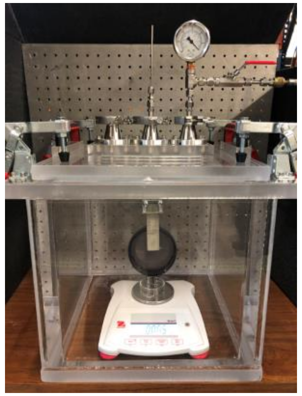
The wick with the best performance

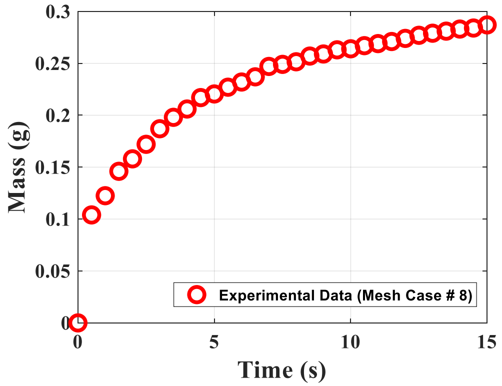
composite wick structures were characterized

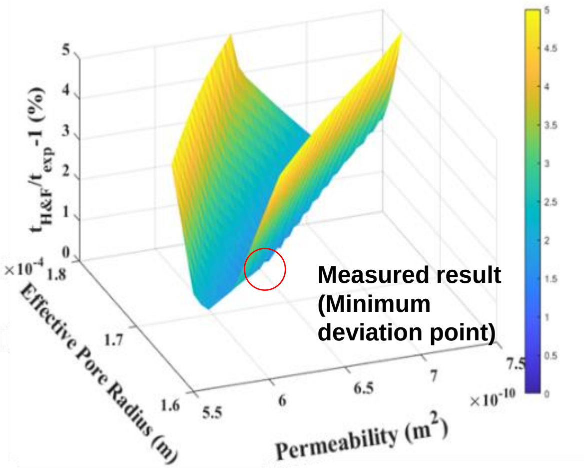
Case #	Total number of layers	Mesh composition			Measurement result			
		100-mesh (inside layer)	400-mesh (middle layer)	60-mesh (outside layer)	Porosity (ε [−])	Permeability (K [μm^2])	Effective Pore Radius (r_{eff}[mm])	$\frac{K}{r_{eff}}$ [μm]
1	6	6	0	0	0.642	0.815× 10^3	0.266	3.064× 10^3
2		0	6	0	0.767	0.825× 10^3	0.232	3.556× 10^3
3		0	0	6	0.626	0.745× 10^3	0.419	1.778× 10^3
4		2	2	2	0.634	0.985× 10^3	0.252	3.909× 10^3
5		1	3	2	0.653	1.435× 10^3	0.213	6.737× 10^3
6		2	3	1	0.667	1.205× 10^3	0.264	4.564× 10^3
7		2	1	3	0.637	0.300× 10^3	0.188	1.596× 10^3
8		3	2	1	0.671	0.635× 10^3	0.169	3.757× 10^3
9		3	1	2	0.682	1.080× 10^3	0.284	3.803× 10^3

Permeability and **effective pore radius** measurement









The method by Holley and Faghri (2005) is used.

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➢ Experiments at TAMU

- Wick Characteristics Experiment
- **Gap Effect Experiment**
- Capillary Rising Modeling
- Heat Pipe Fabrication and Experiment
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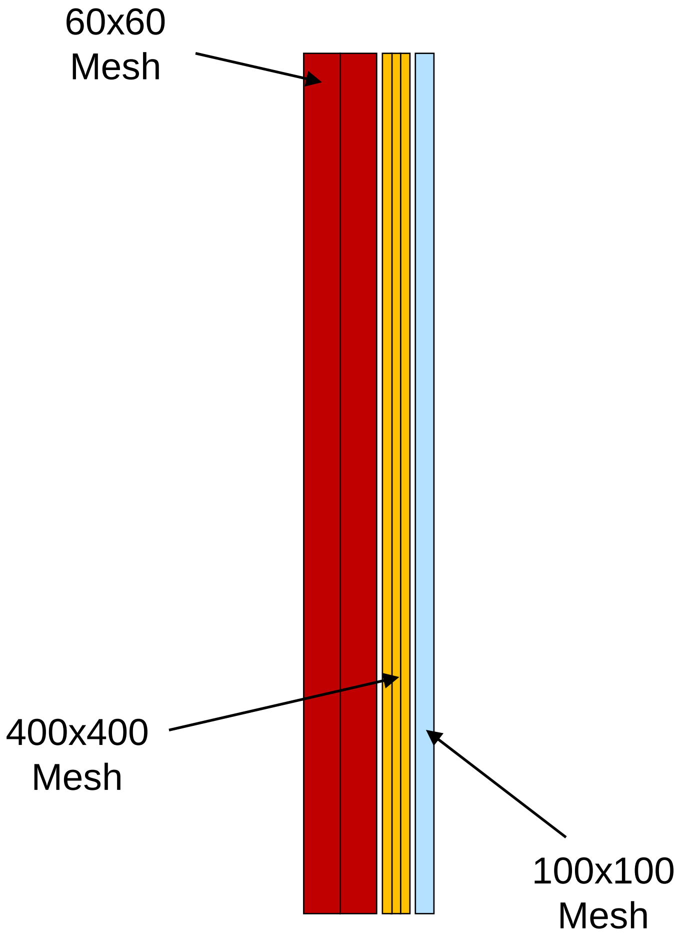
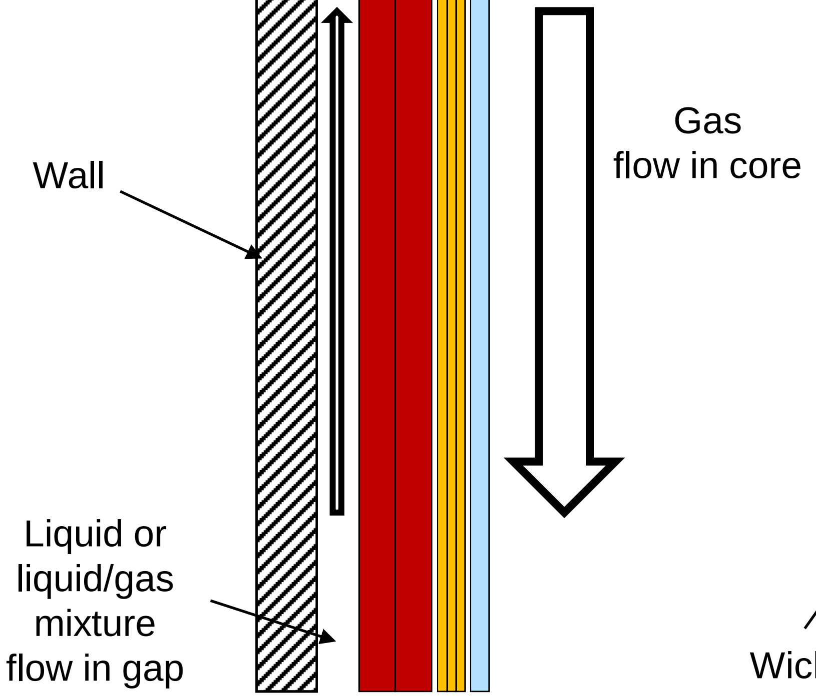
Wall Effect Investigation

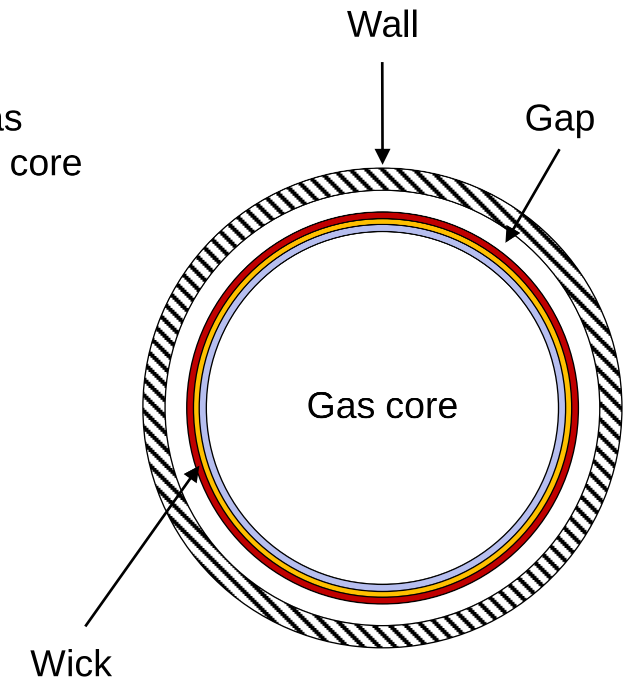
Tested case



Actual case inside heat pipe

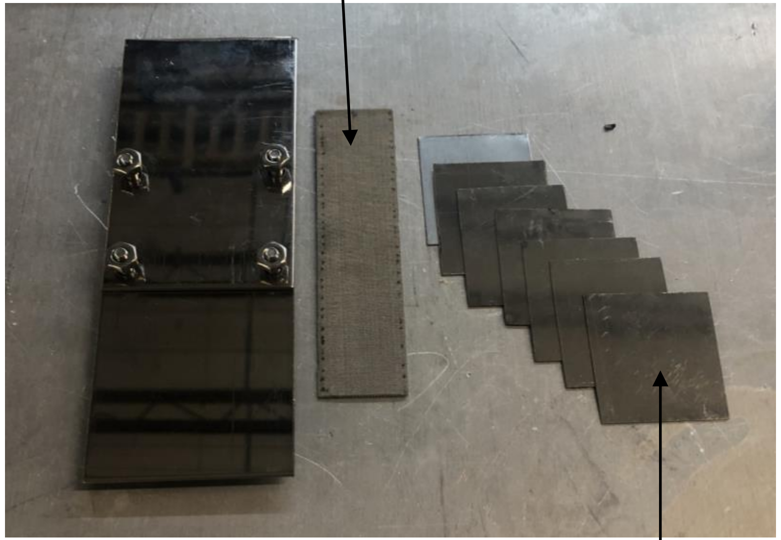


In SAFE-30 report, the gap of the heat pipe manufactured by LANL appeared as 0.7 mm. We want to check the effect of the gap to the wick characteristics.

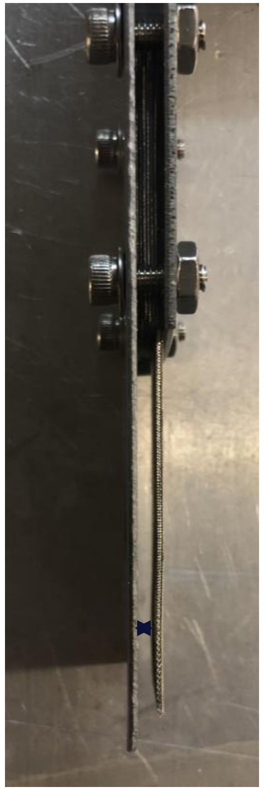


Wall Effect Experimental Setup

Wick type #5
6-layered composite screen mesh



Shim structures with varying thickness
to control the size of the gap



A Simple setup was prepared to measure permeabilities of a wick structure with different sizes of gap (0.0 mm ~ 30.0 mm) between stainless steel wall and the screen mesh.

The same method with previous study was utilized.

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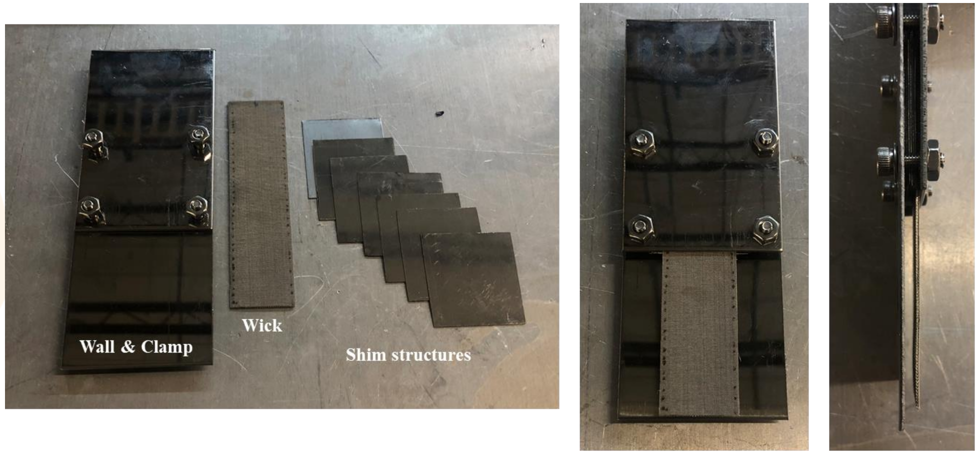
Gap Effect Experiment

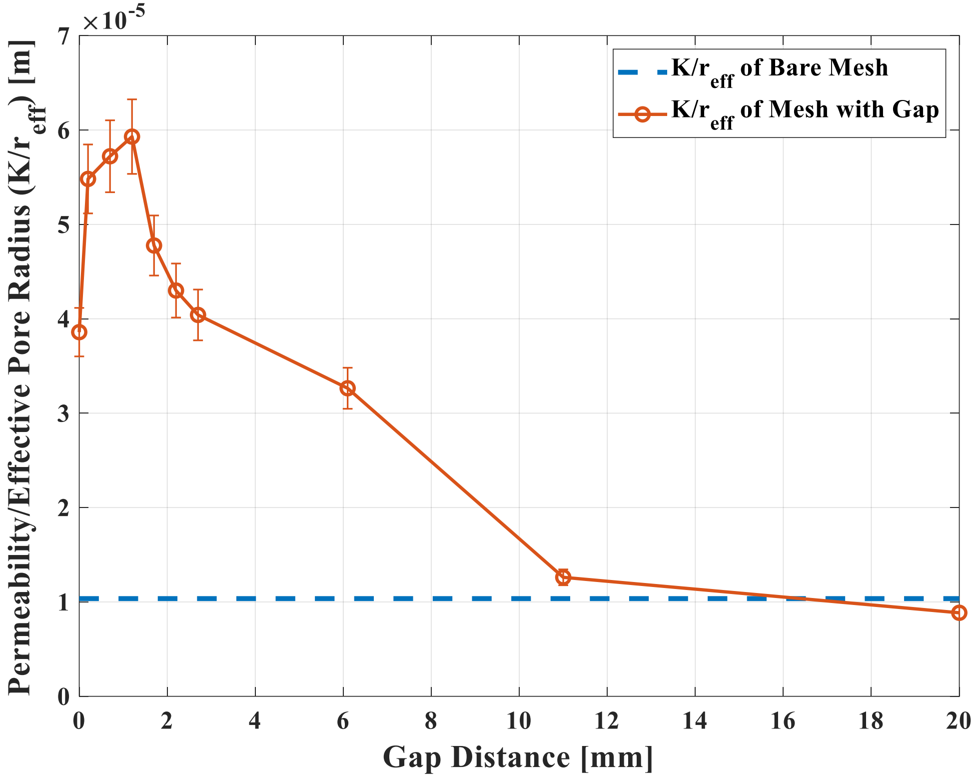
Wick assembly with adjustable gap between the wall

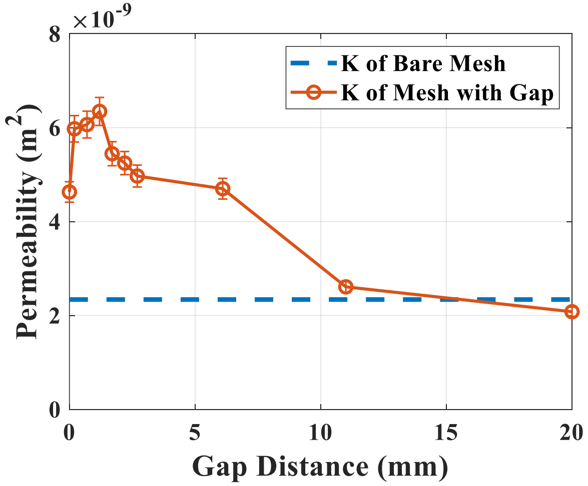


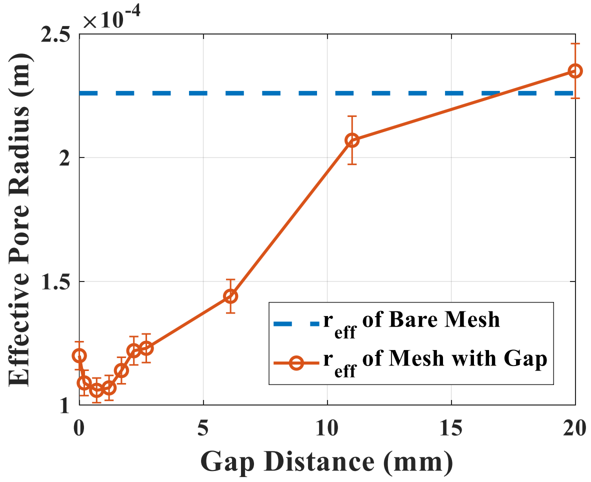
Front view

Side view

Wick samples were prepared to measure permeabilities and effective pore radius with different sizes of gap (0.0 mm ~ 20.0 mm) between stainless steel wall and the screen mesh.







Optimal distance of the gap for the annular type heat pipe was found

The result of the measurement is plotted vs. the gap distance.
An interesting trend can be found from the result. The $^{K}/_{R_{eff}}$ increases as the gap increase, a peak at 0.7 to 1.2 mm is observed. As the gap continues to increase, the permeability falls the bare mesh case.

MRP Microreactor Program

➢ Experiments at TAMU

- Wick Characteristics Experiment
- Gap Effect Experiment
- **Capillary Rising Modeling**
- Heat Pipe Fabrication and Experiment
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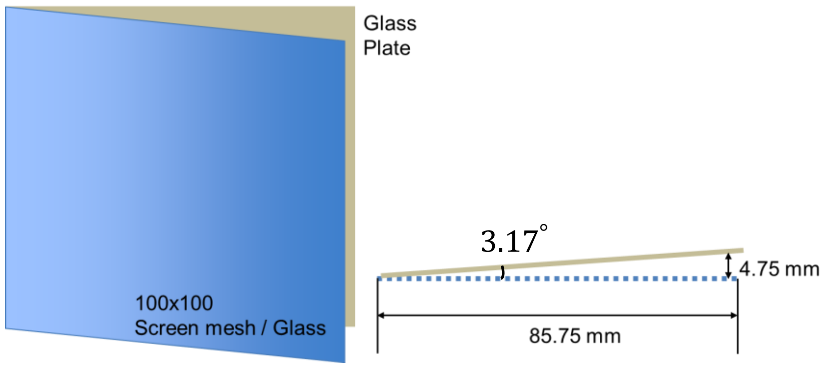
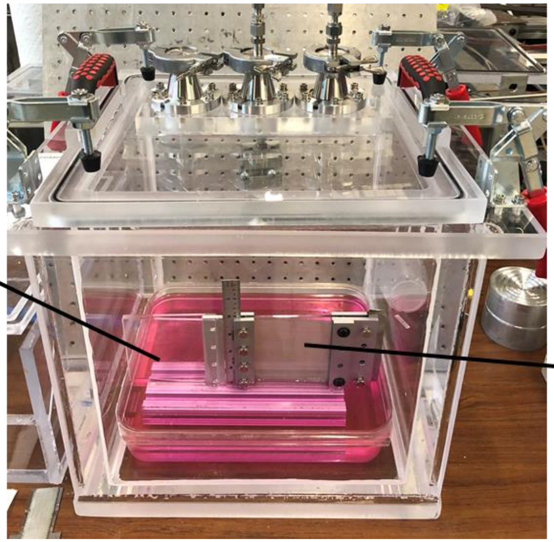
Capillary Rising Modeling

Contact angle of ethanol on a glass surface

Experimental setup of angled mesh-plate experiment

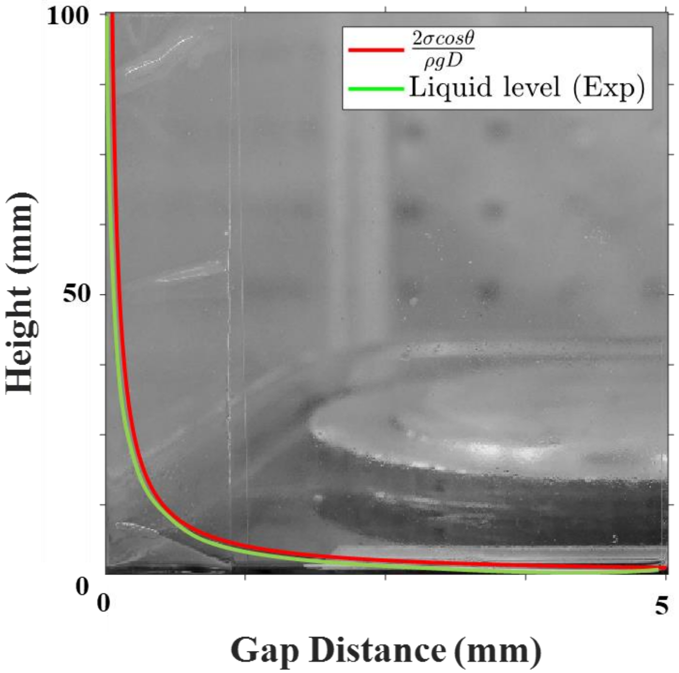


Glass/ Glass

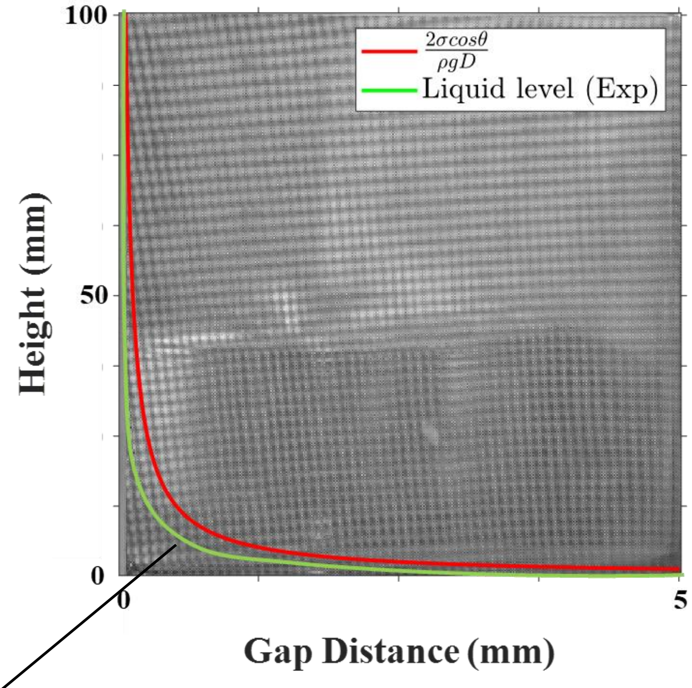


Glass/ Mesh

Glass/Glass experiment ($\theta = 30^{\circ}$)



Glass/Mesh experiment ($\theta = 30^{\circ}$)



The rising height of the liquid in a gap between solid/mesh differs from solid/solid case. There is no study on the capillary pressure acting on solid surface/mesh surface. The result might be useful to model the gap effect.

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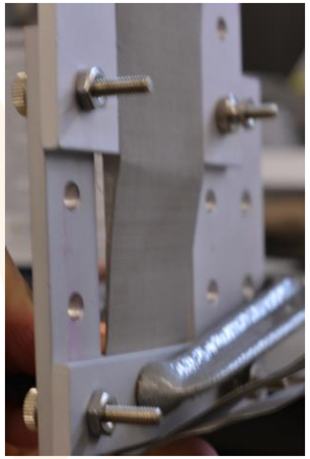
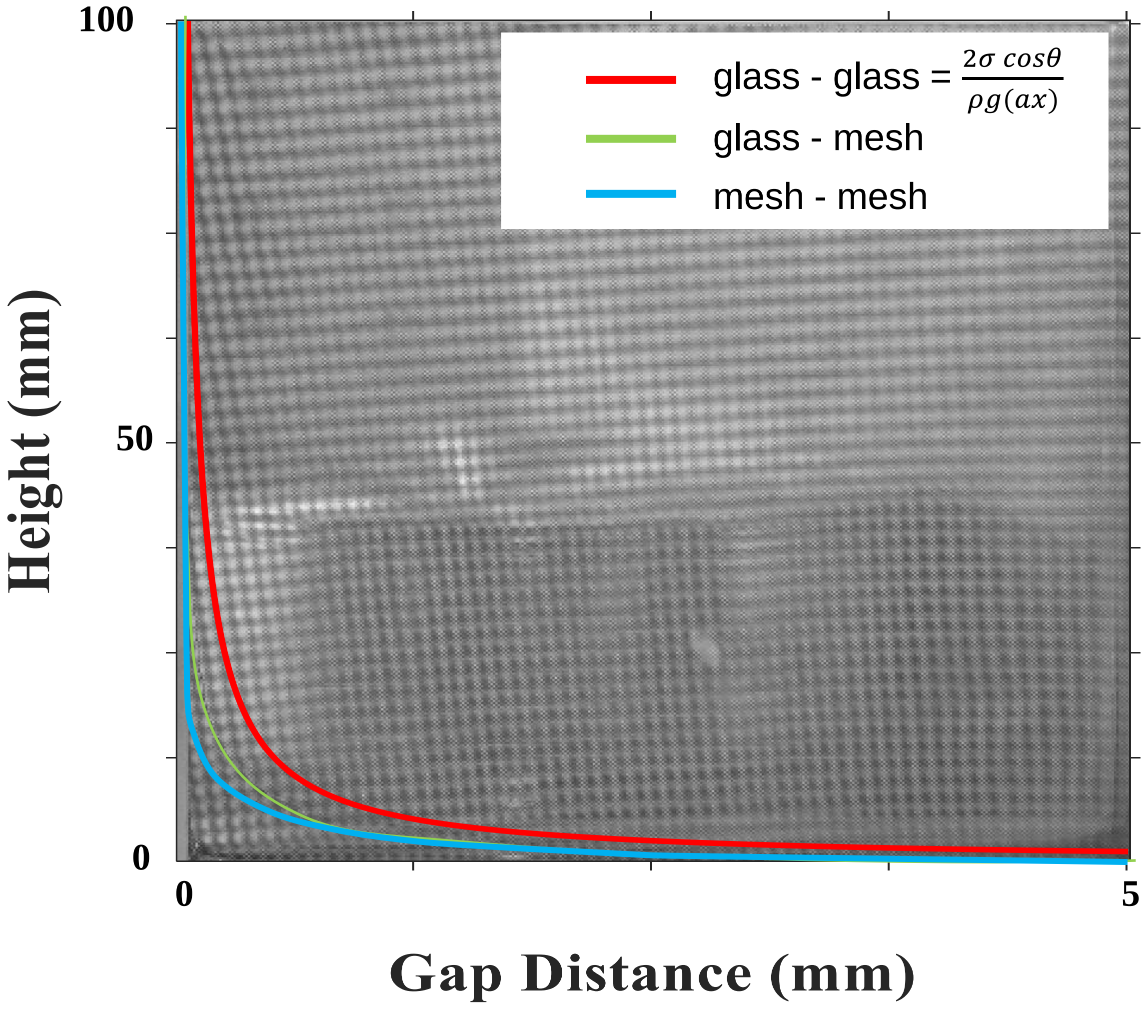
Capillary Rising Modeling

Mesh-mesh Exp.





Mesh-mesh graph is smaller than glass-mesh.
According to the formula, height is
$h = \frac{\sigma\,(cos\theta_0 + cos\theta_1)}{\rho g(w)}$
(where θ_0 = glass contact angle and θ_1 = mesh contact angle),
Therefore,

$cos\theta_1 < cos\theta_0$, $\theta_0 < \theta_1$

Glass contact angle with ethanol θ_0 is about 30°($\pi/6$), then Mesh contact angle with ethanol would be larger than 30°

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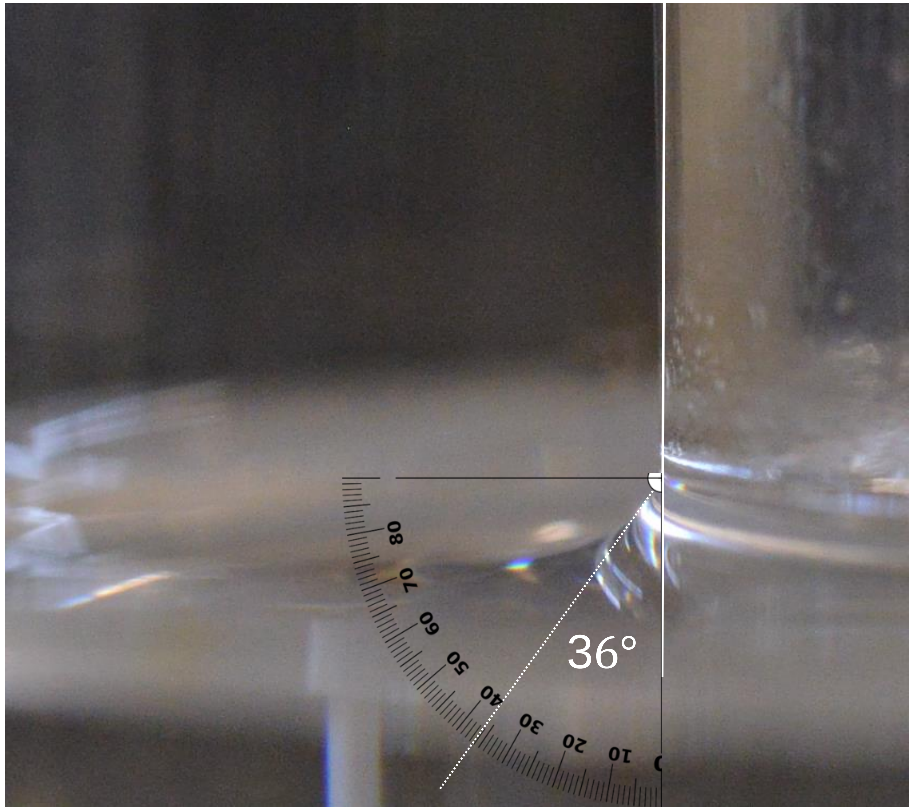
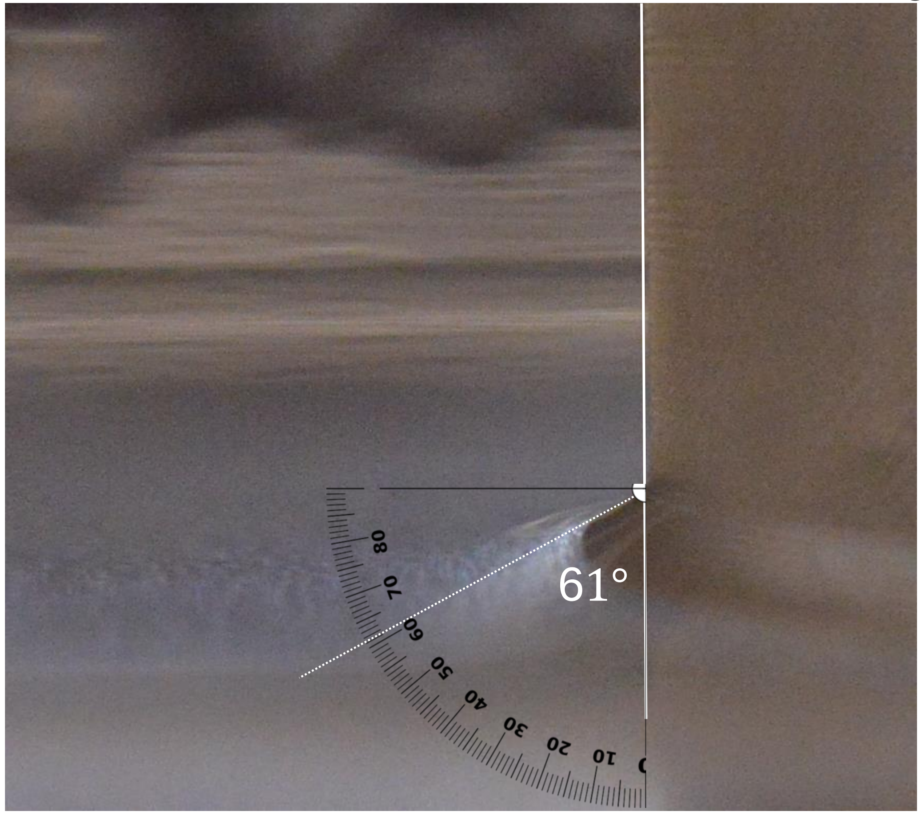
Contact Angle Measurement

Glass – Ethanol contact angle



Stainless steel mesh – Ethanol contact angle



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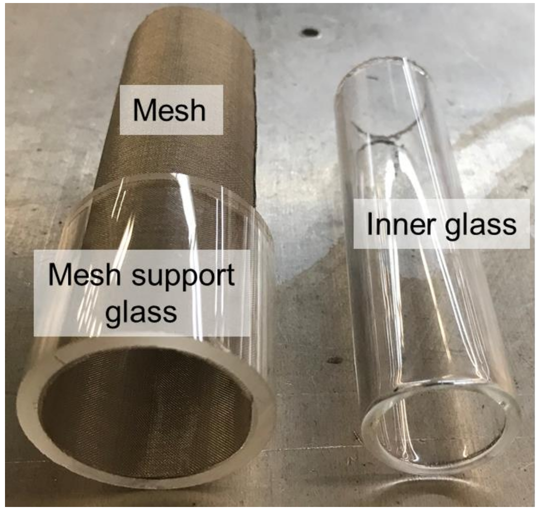
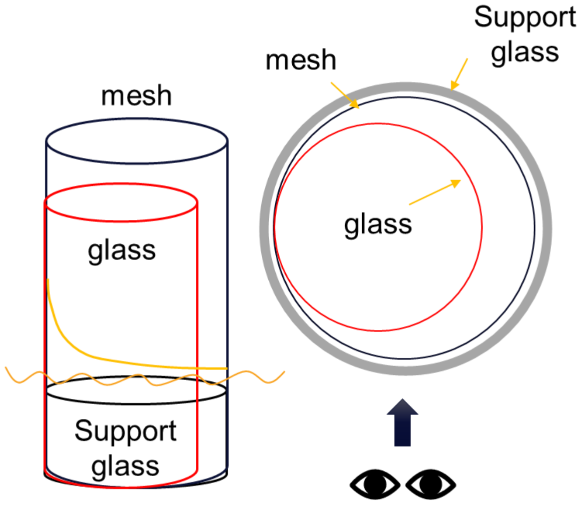
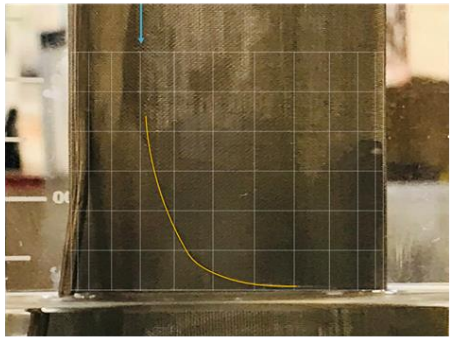
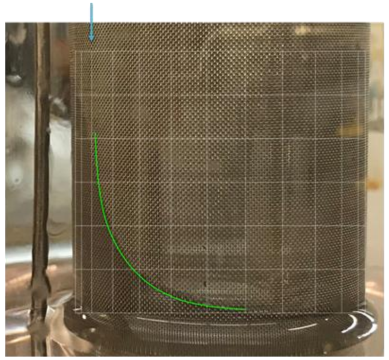
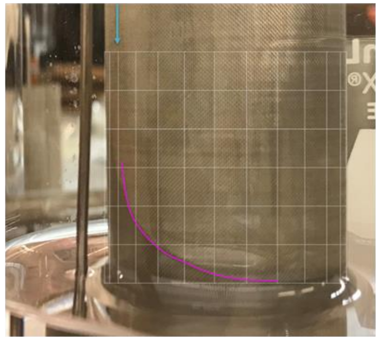
Curvature Effect

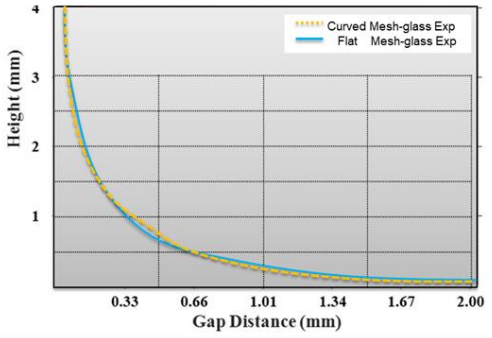


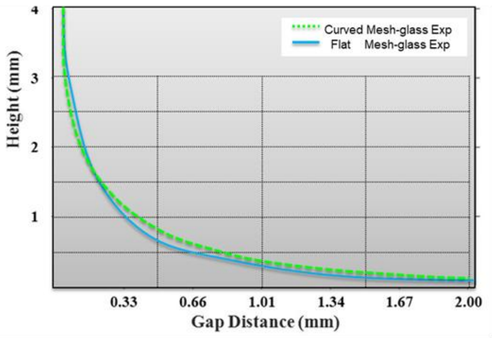


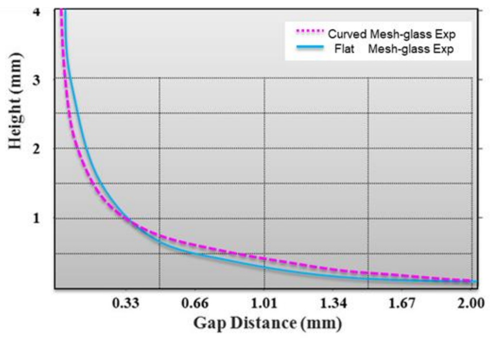












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➢ Experiments at TAMU

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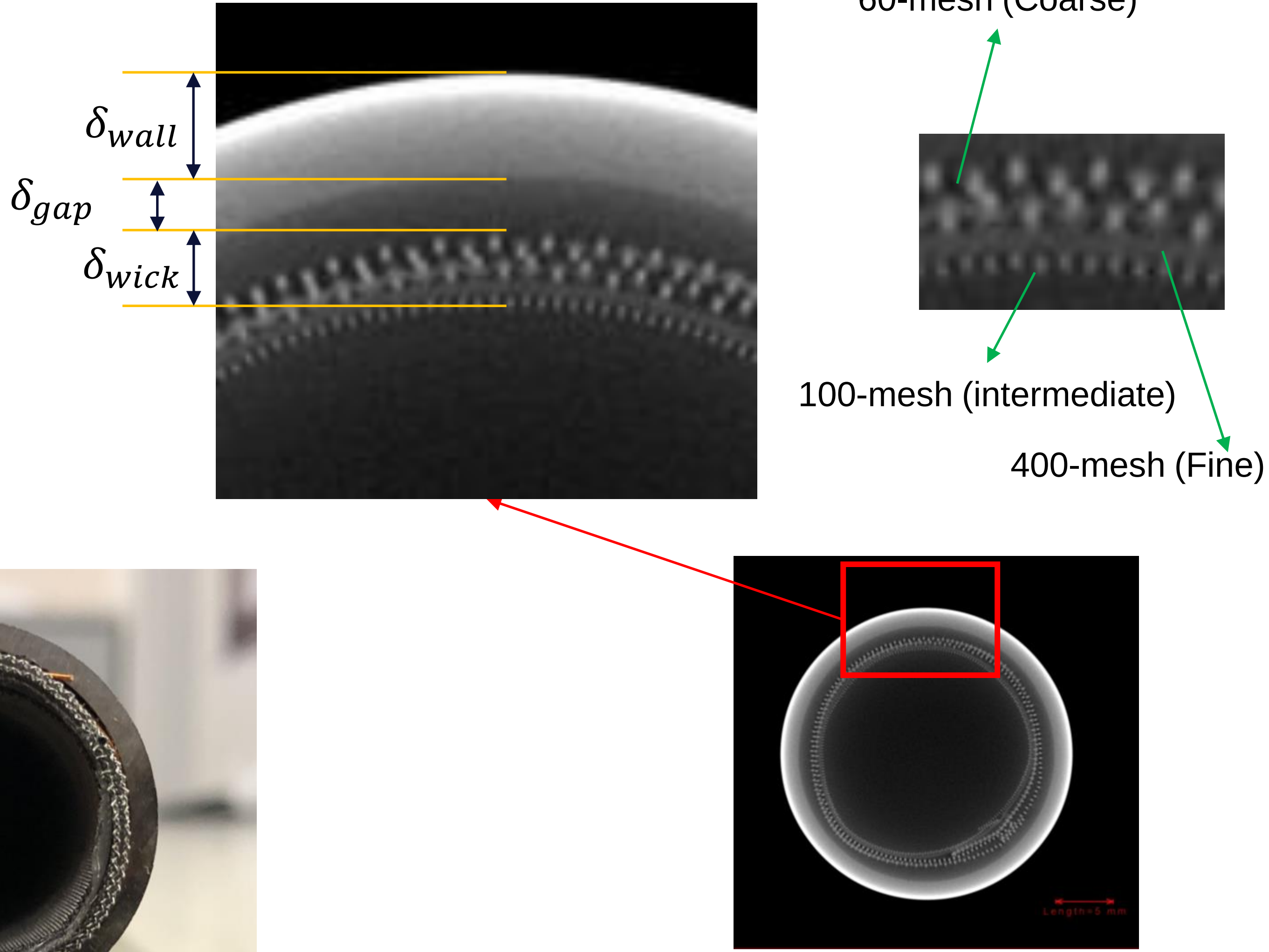
Stainless Steel Heat Pipe

Multi-layered composite screen wick mesh was fabricated.

Micro CT scanning of the heat pipe cross-section



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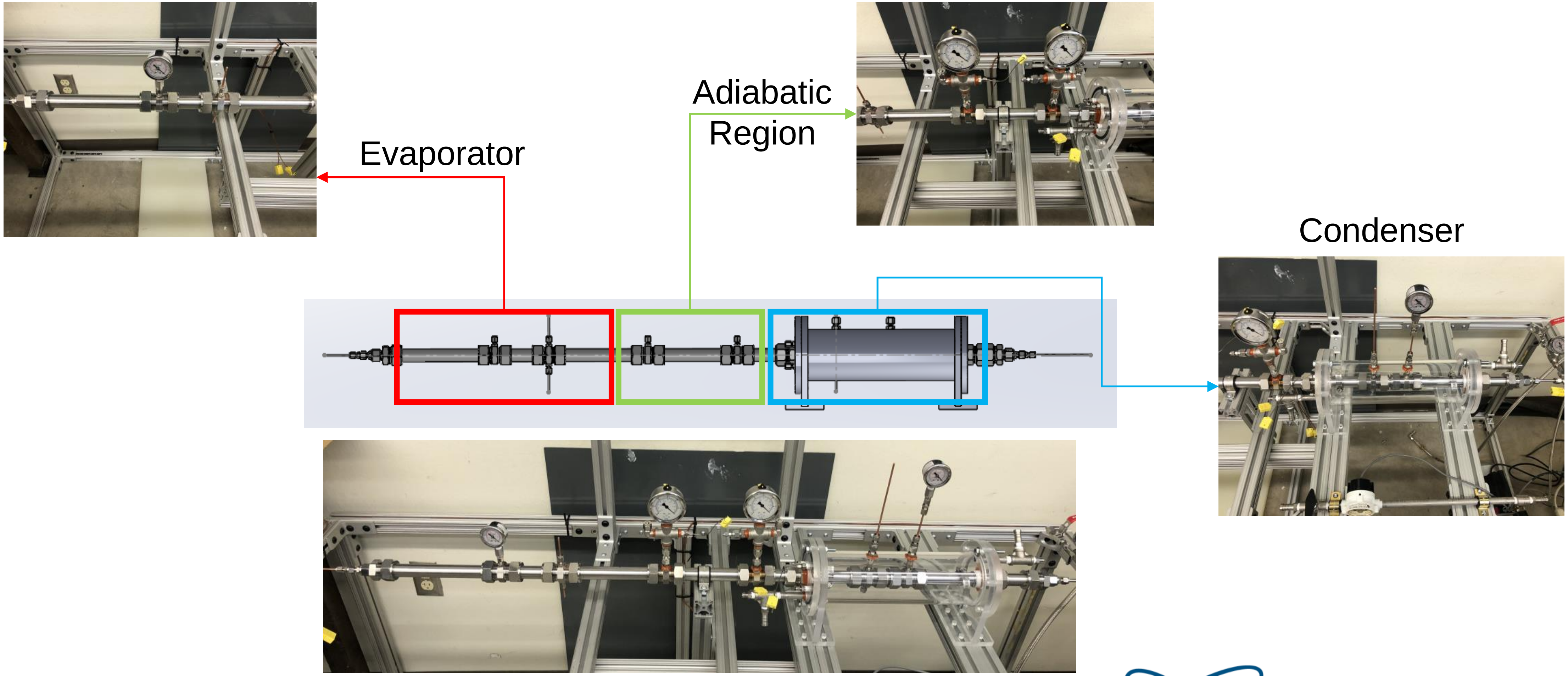
Heat Pipe Experimental Facility



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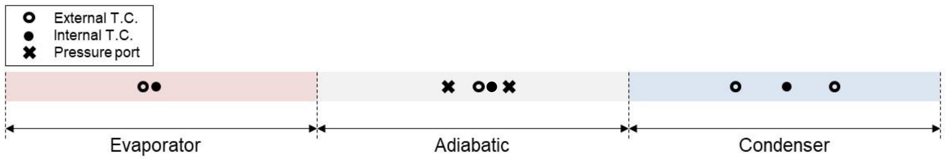
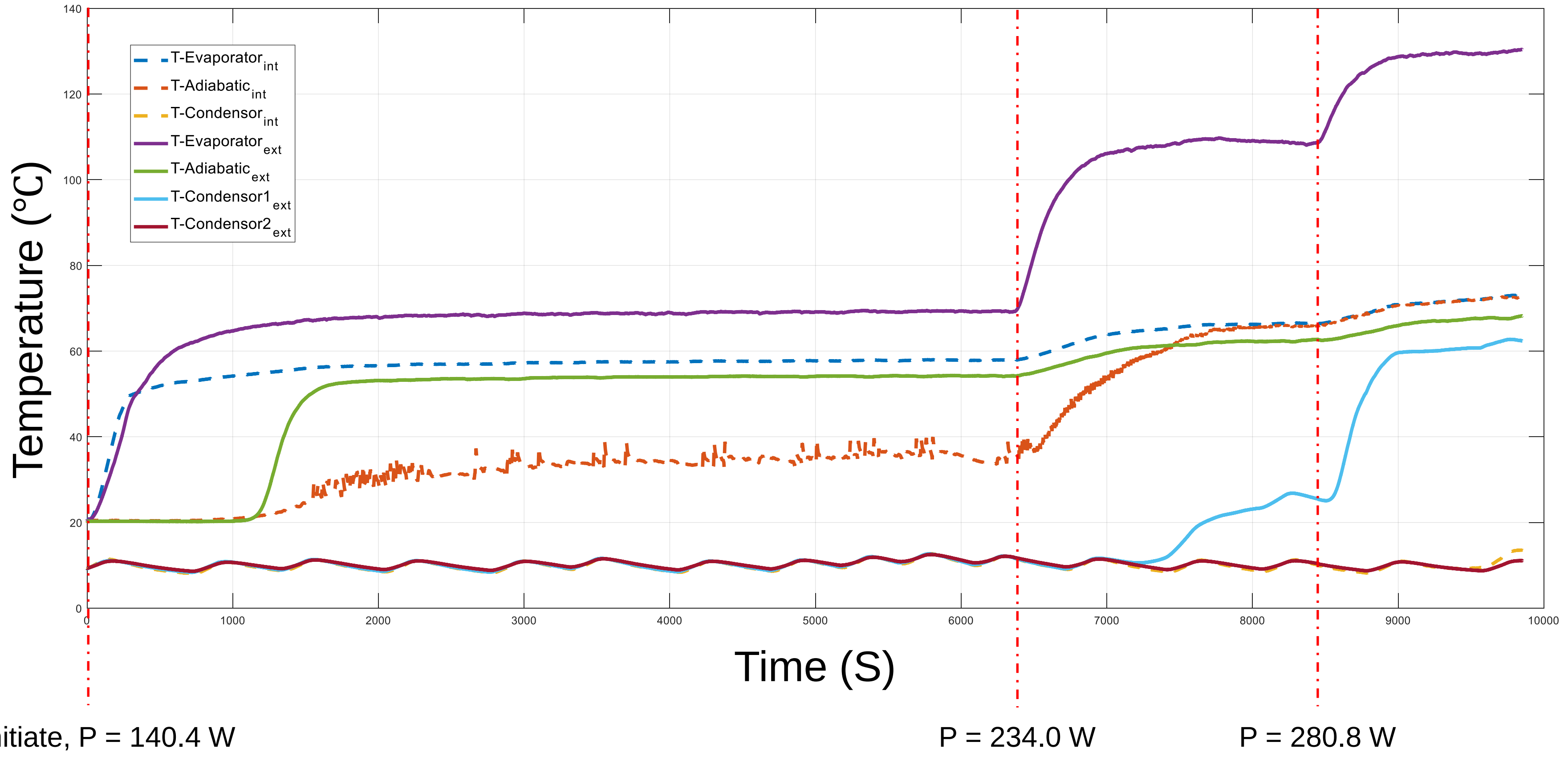
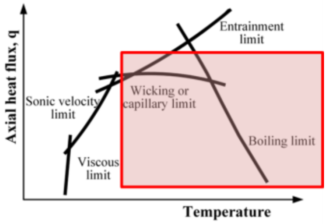
Shakedown Test



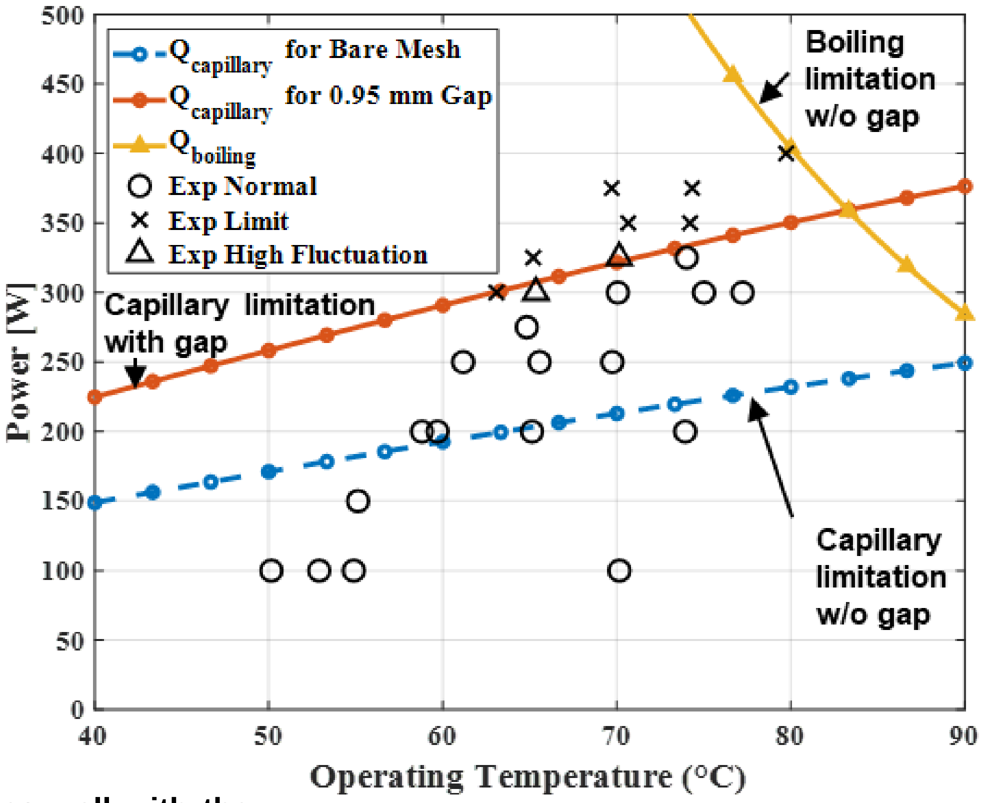


Heat Pipe Fabrication and Experiment



$$Q_{capillary.gap} = G \cdot Q_{capillary} = G \frac{2\sigma}{r_{eff}} \frac{KA_{wick} h_{lv} \rho_l}{\mu_l L_{eff}}$$

Gap Distance [mm]	G [-]
0	1.00
0.2	1.42
0.7	1.48
1.2	1.54
1.7	1.24
2.2	1.11
2.7	1.05



The operating limitation of the heat pipe matches well with the prediction from the result of the wick characterization and gap effect experiment.

➢ Experiments at TAMU

- Wick Characteristics Experiment
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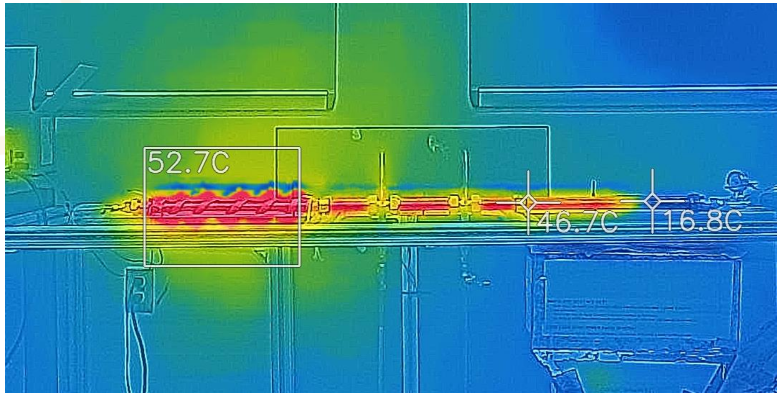
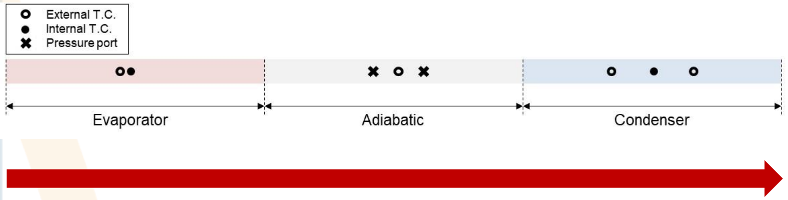
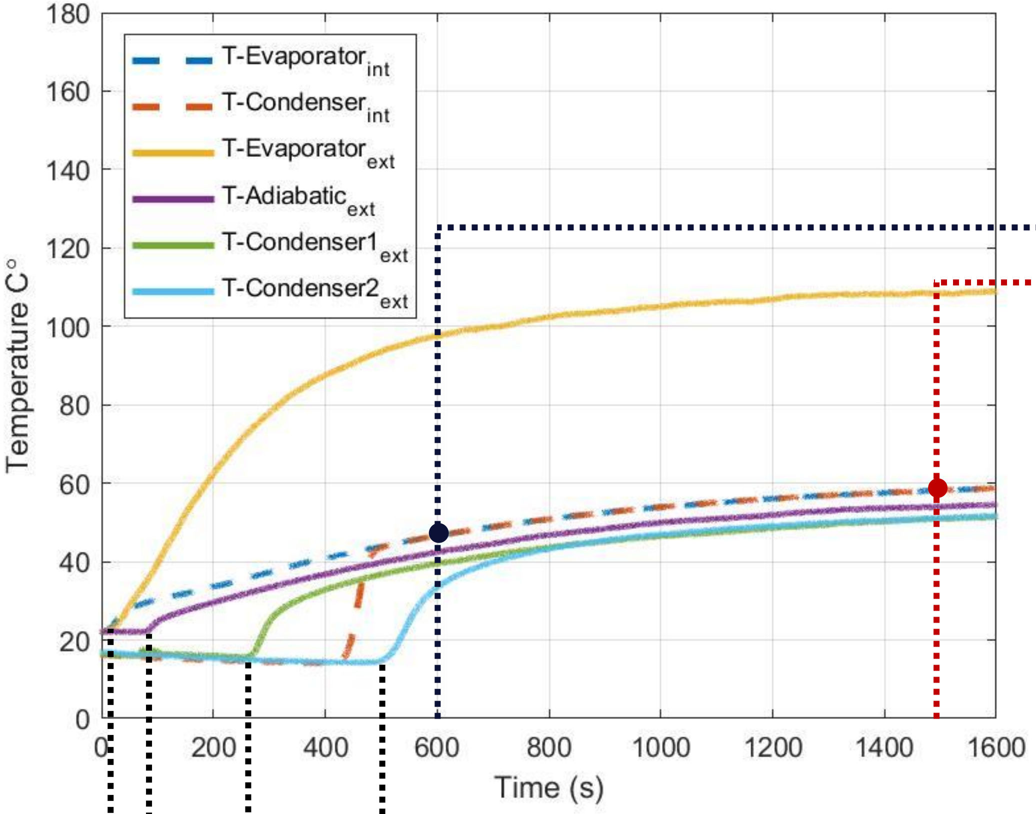
Temperature Measurement System





Heat propagation



Temperature (C)	Pressure (MPa)	Density (kg/m3)
0.028556	0.00061248	999.79
46.974	0.010612	989.33
60.711	0.020612	982.79
69.560	0.030612	977.98
76.223	0.040612	974.08
81.620	0.050612	970.75
86.187	0.060612	967.82
90.161	0.070612	965.19
93.691	0.080612	962.79
96.873	0.090612	960.57
99.777	0.10061	958.51

Evaporator

Adiabatic Region

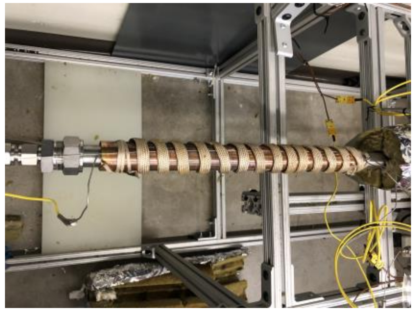
Condenser 1

Condenser 2

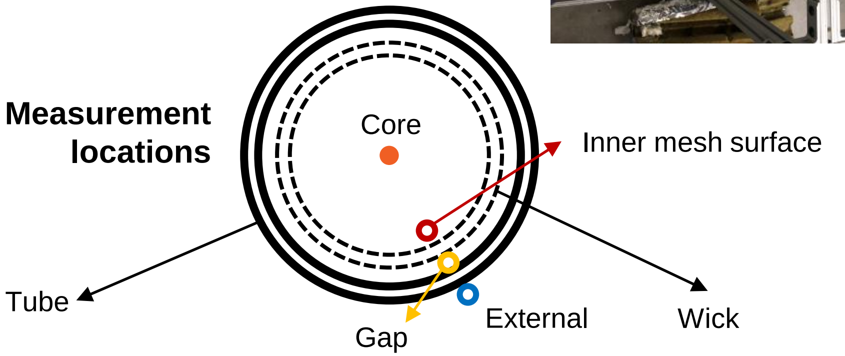
MRP Microreactor Program

Distributed Temperature Sensing (DTS)

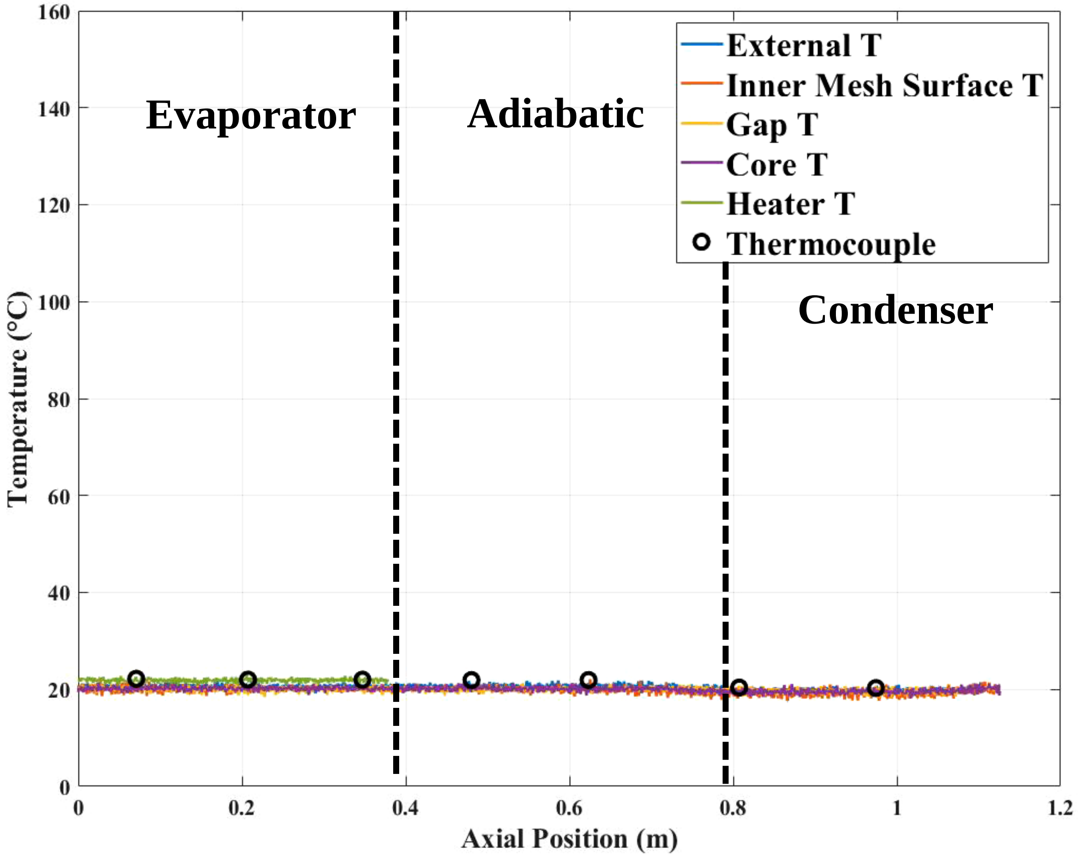
Heater was wrapped on the copper tube for uniform heat transfer to the heat pipe.



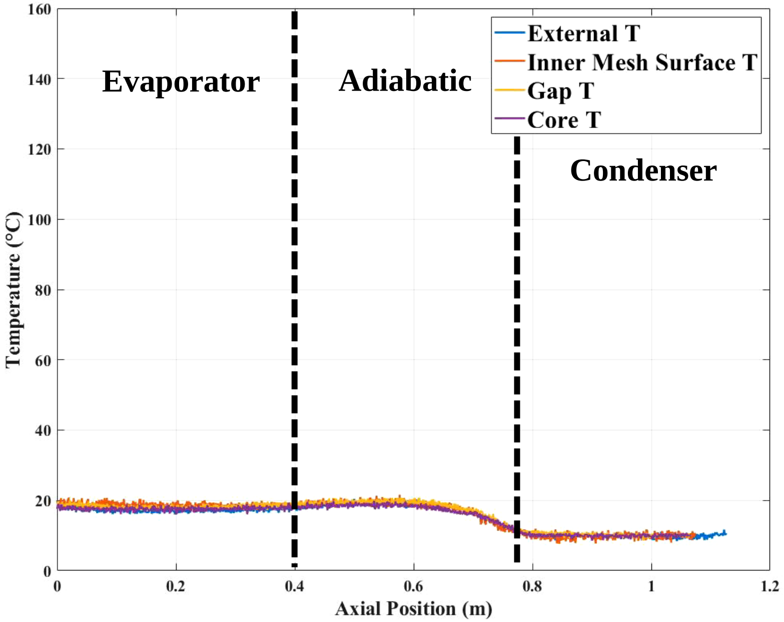
Measurement locations



Slow start (30W, ~60 mins) of the heat pipe



Rapid start (75W, ~60 mins) of the heat pipe



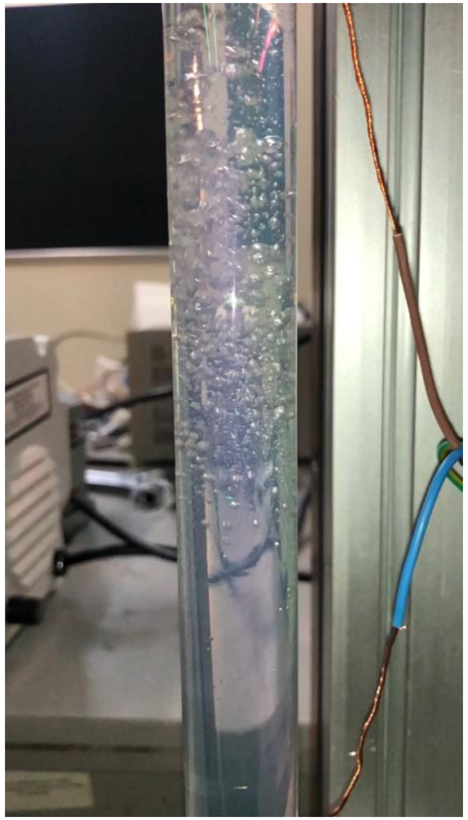
➢ Experiments at TAMU

- Wick Characteristics Experiment
- Gap Effect Experiment
- Capillary Rising Modeling
- Heat Pipe Fabrication and Experiment
- Heat Pipe Measurement
- **Heat Pipe Visualization**

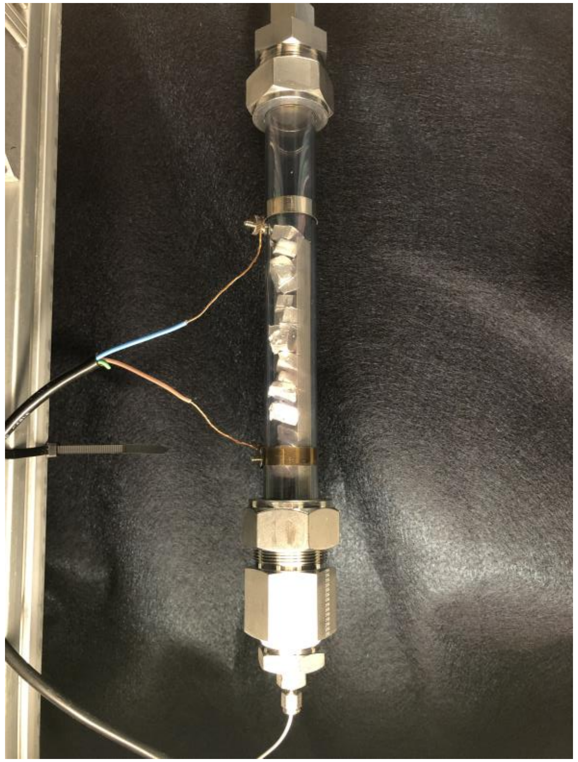
MRP Microreactor Program

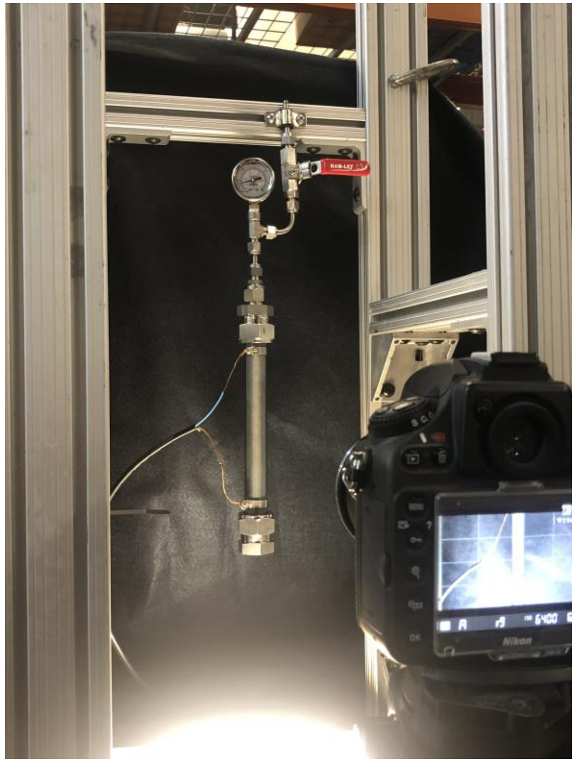
Flow Visualization of Liquid Metal

TAMU has a capability of transparent heating up to 700 ℃ and ~101 kW/m^2 of heat flux.



Water boiling experiment using transparent heater.



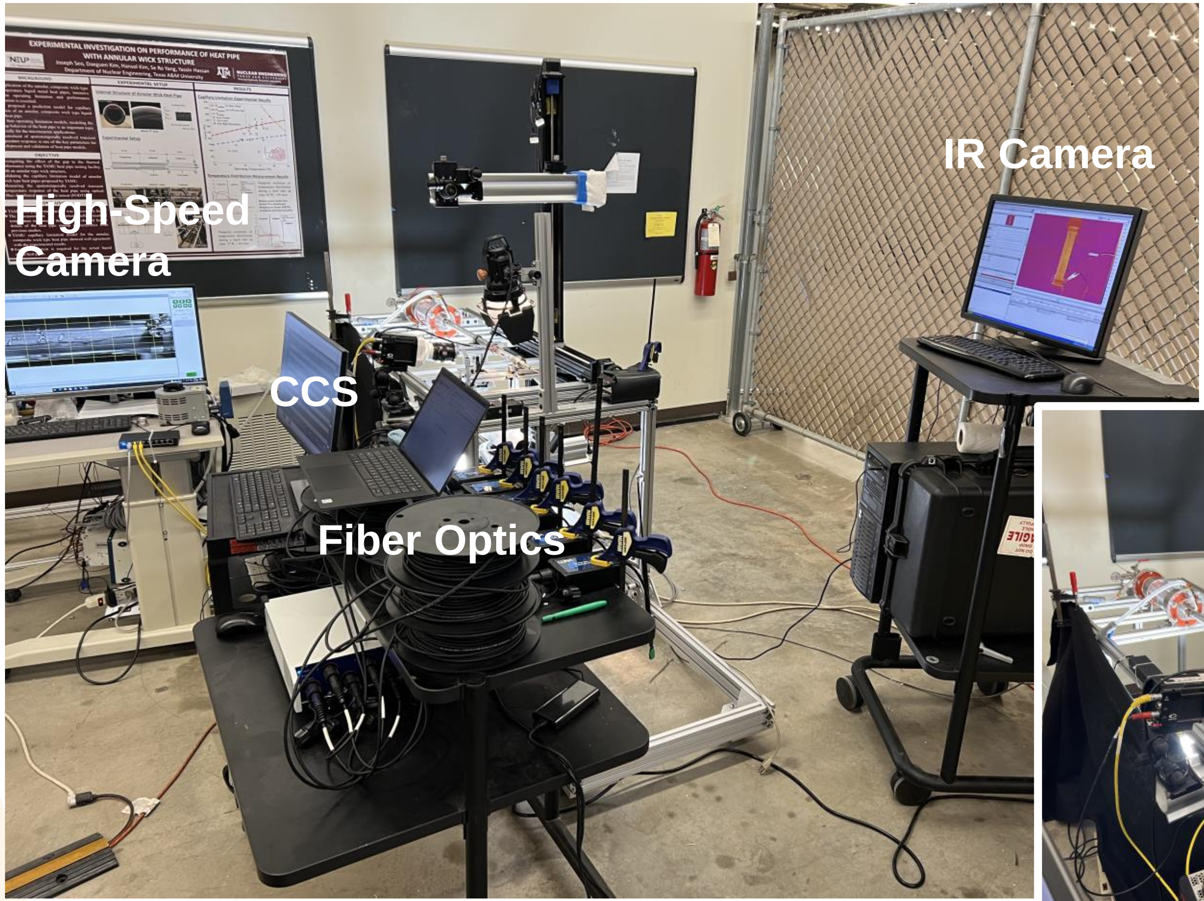


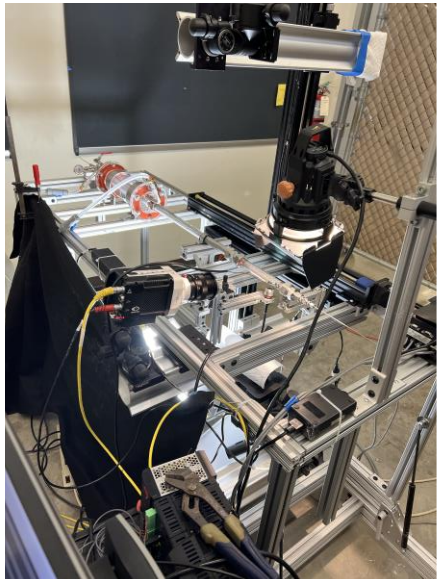
TAMU is being conducted to perform melting/boiling experiment using the transparent heater.

The experiment will allow to obtain information about flow behavior of liquid metal at different operating status of the heat pipe.

MRP Microreactor Program

Heat Pipe Visualization Experimental Setup

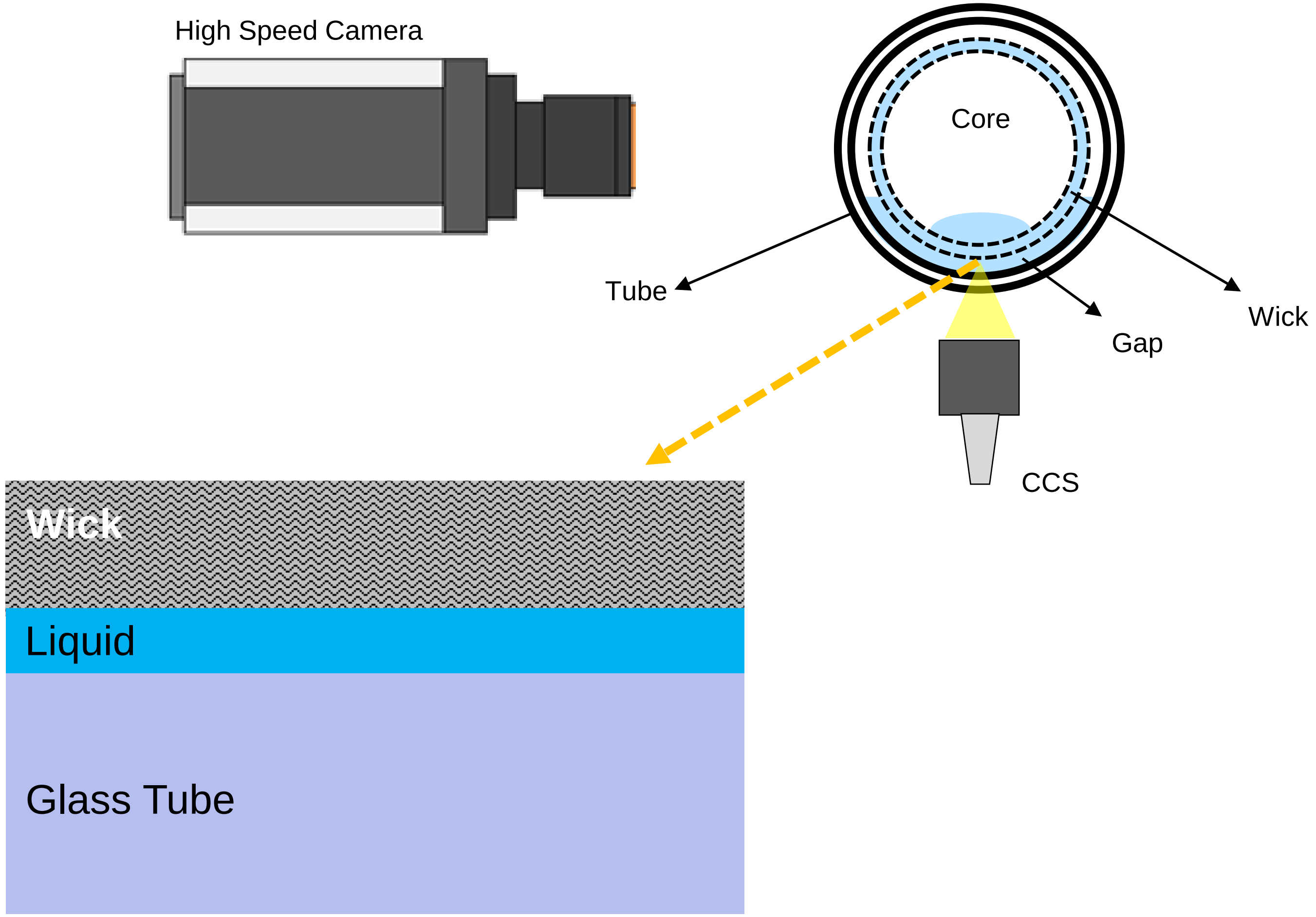


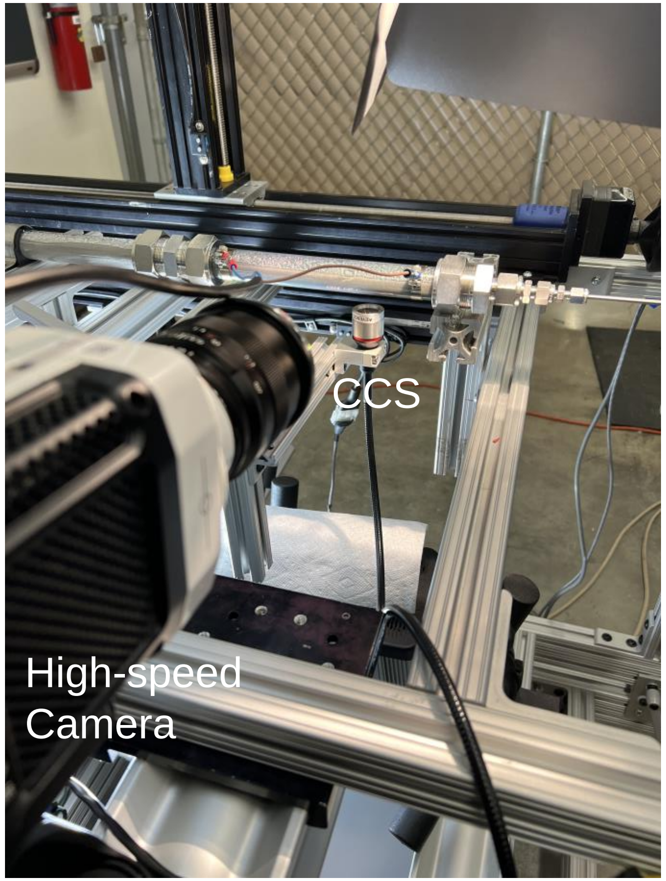


- Visualization using high speed camera and IR camera is conducted.
- Temperature measurement using fiber optical sensor and IR camera is implemented.
- Confocal Chromatic Sensor (CCS) is applied to measure the liquid film behavior.
- 4 gas cylinders were added to adjust inclination angle.

MRP Microreactor Program

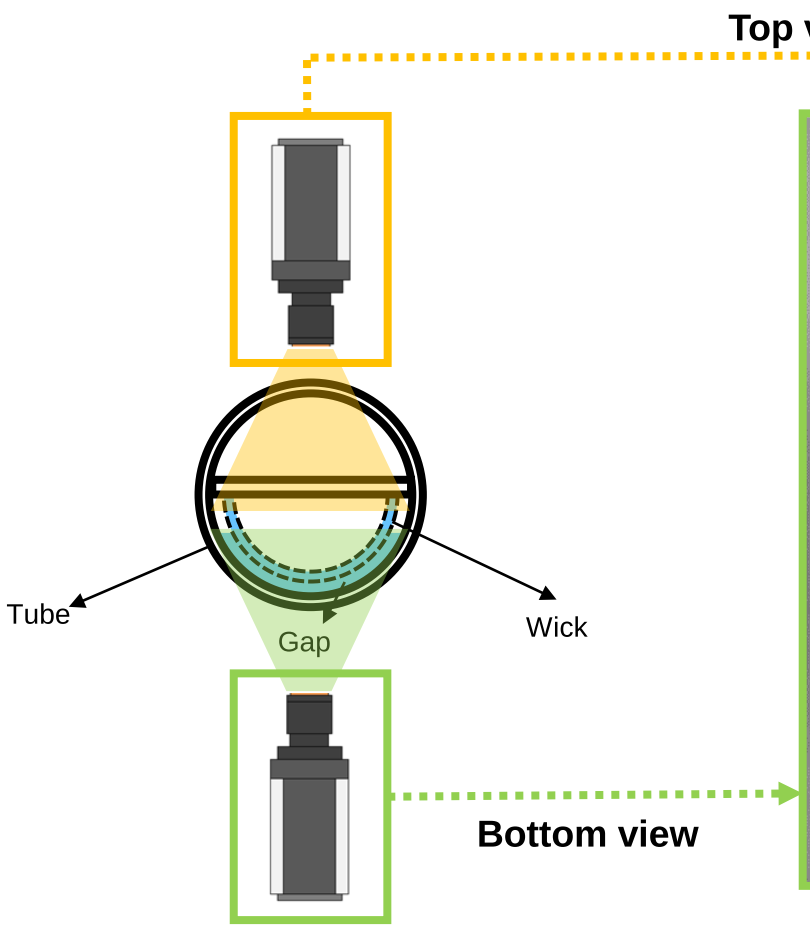
CCS Measurement & High-Speed Images

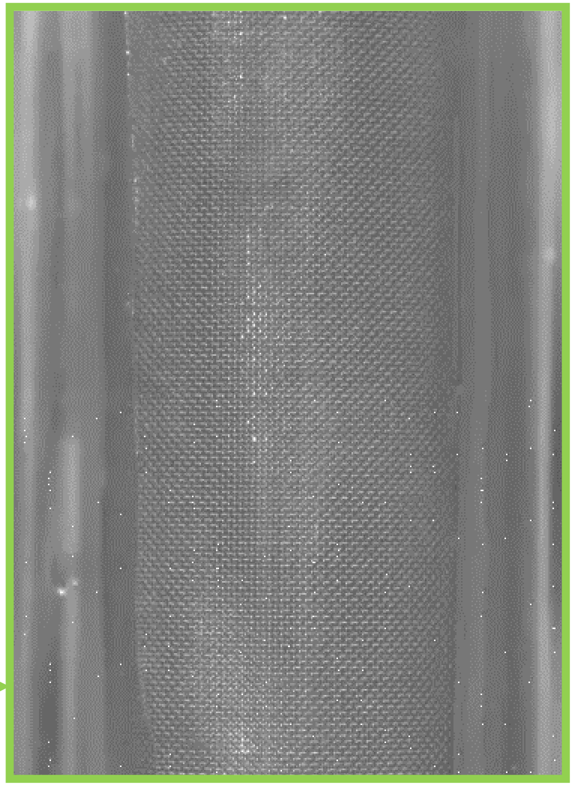


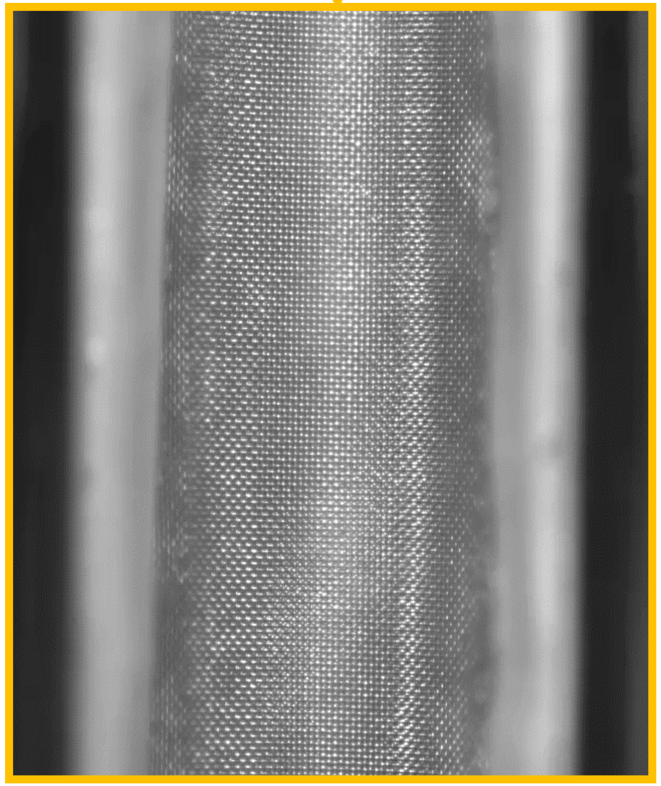


MRP Microreactor Program

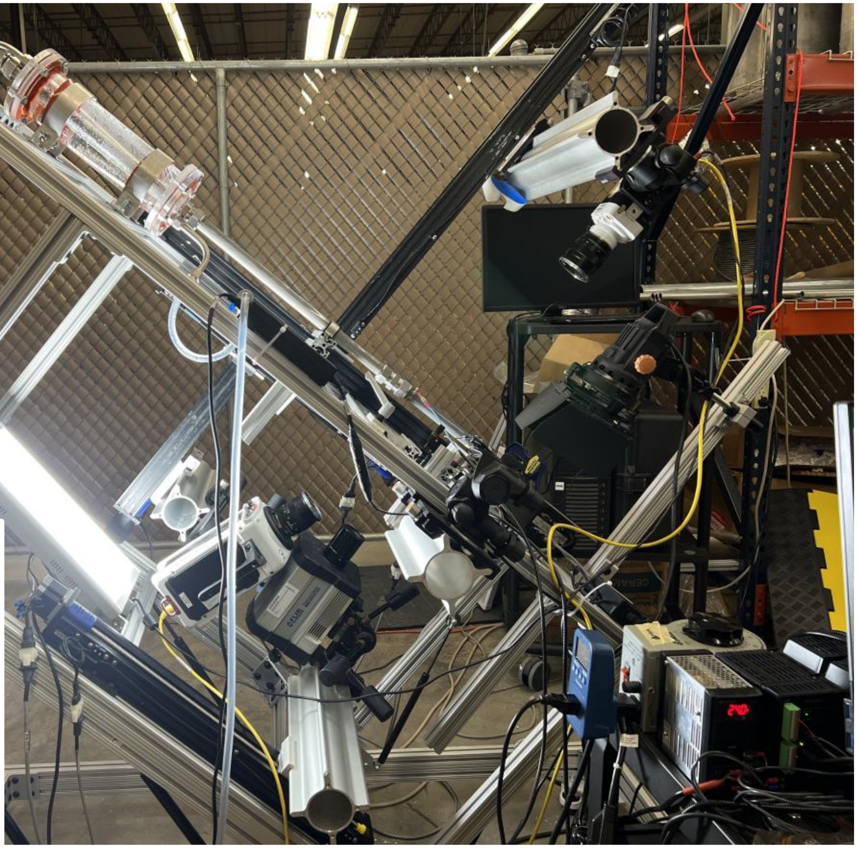
Boiling Pattern Inside Heat Pipe – Half Wick Exp

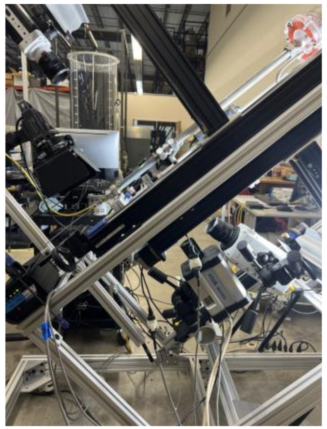




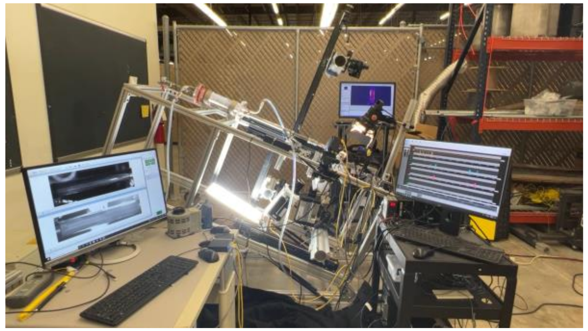


Heat Pipe Visualization with Inclination Angle





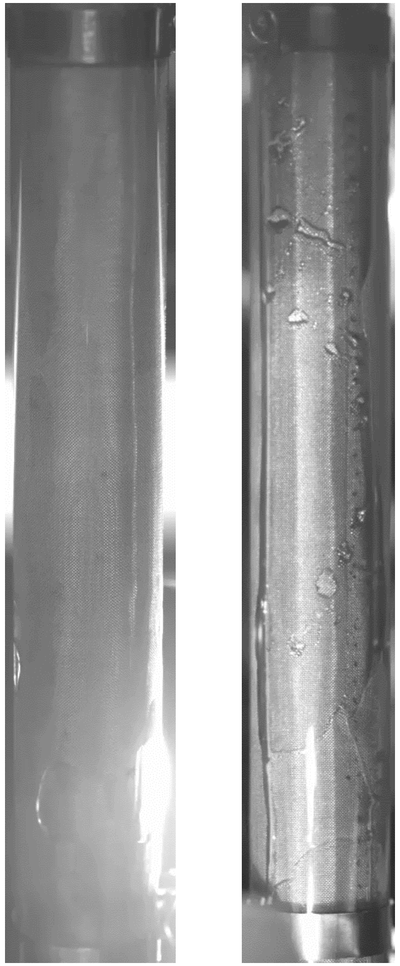
- Visualization of the heat pipe with different inclination angle.
- Temperature measurement using fiber optical sensor and IR camera is implemented.
- Two high-speed camera was set (bottom side and top side)



MRP Microreactor Program

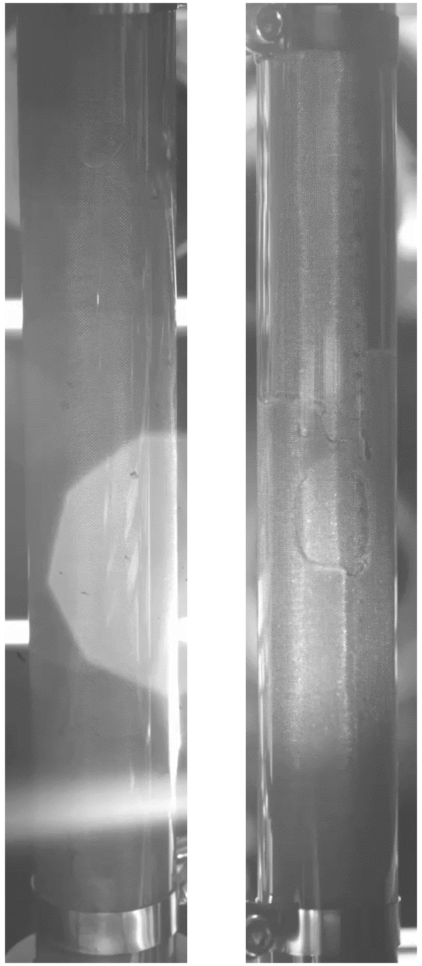
Heat Pipe Visualization Results

Horizontal
0-degree
100W



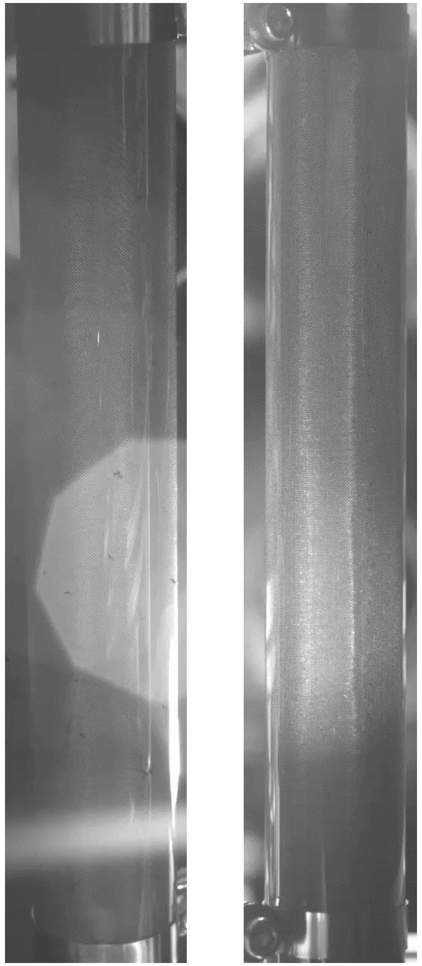
Bottom Top

45-degree
200W



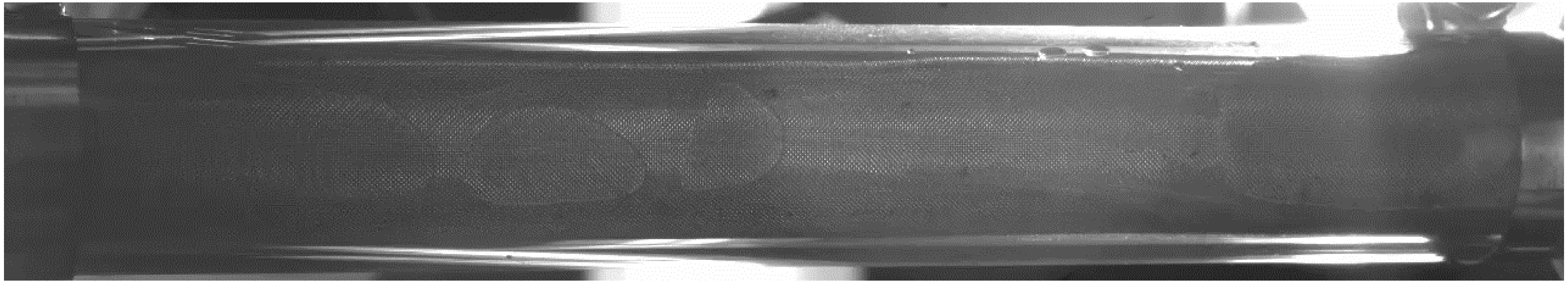
Bottom Top

Vertical
90-degree
200W

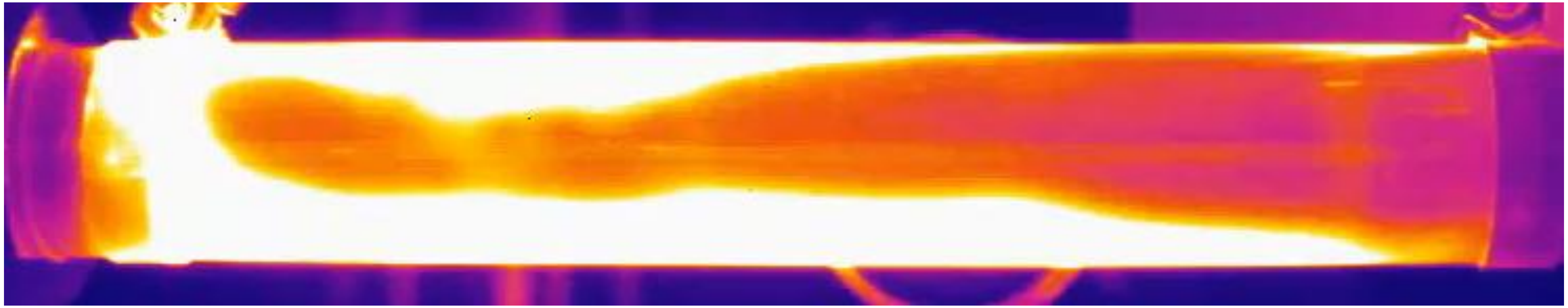


Bottom Top

Heat Pipe Visualization Results - Limitation



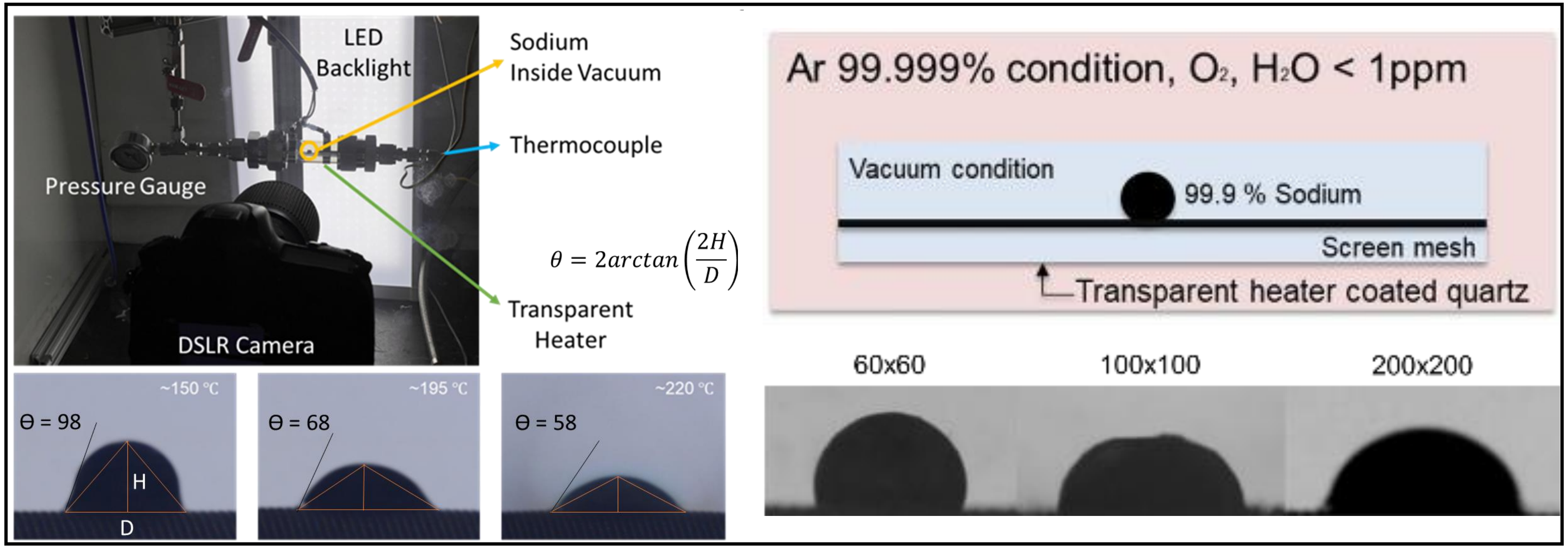
High-speed camera



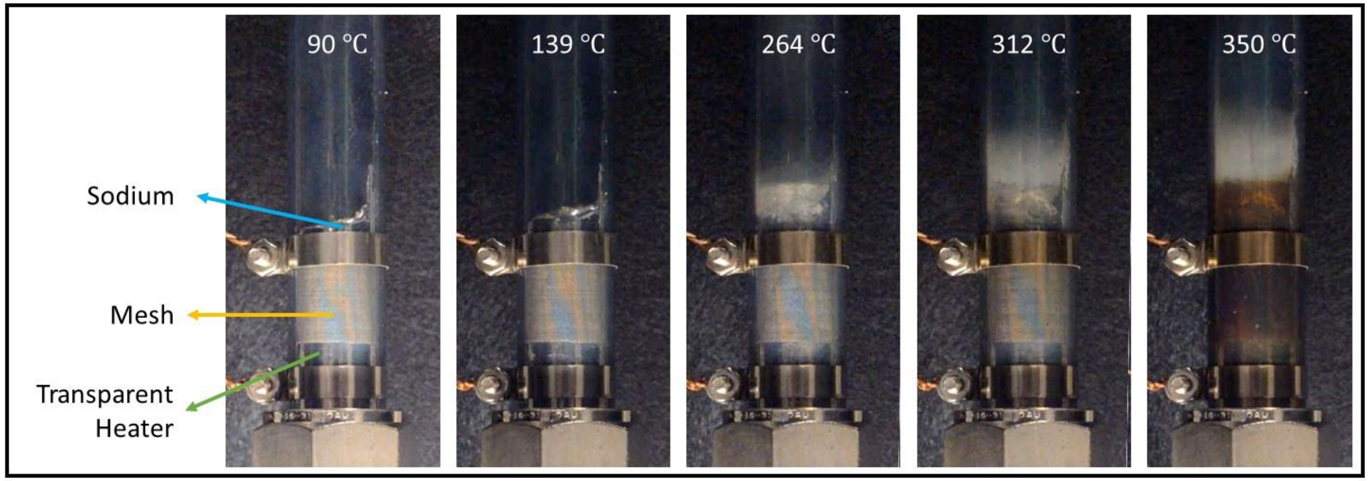
IR camera

200W, 0-degree inclination, rapid start-up

In Progress – Moving on to the Liquid Metal



The contact angle measurement of the liquid sodium with different material (stainless steel plate and meshes) is being conducted in TAMU.



Visualization of melting/boiling of the sodium in a vacuum condition is under the progress.

MRP Microreactor Program

MRP Microreactor Program

Direct heating of chemical catalysts for hydrogen and fertilizer production using Microreactors

Hitesh Bindra (PI) | Associate Professor, Kansas State University

TPOC: Piyush Sabharwall (TAL, MRP)

Direct heating of chemical catalysts for hydrogen and fertilizer production using Microreactors

- Team members

Hitesh Bindra (PI), KSU

Melanie Derby (Co-PI), KSU

Caleb Brooks (Co-PI), Illinois

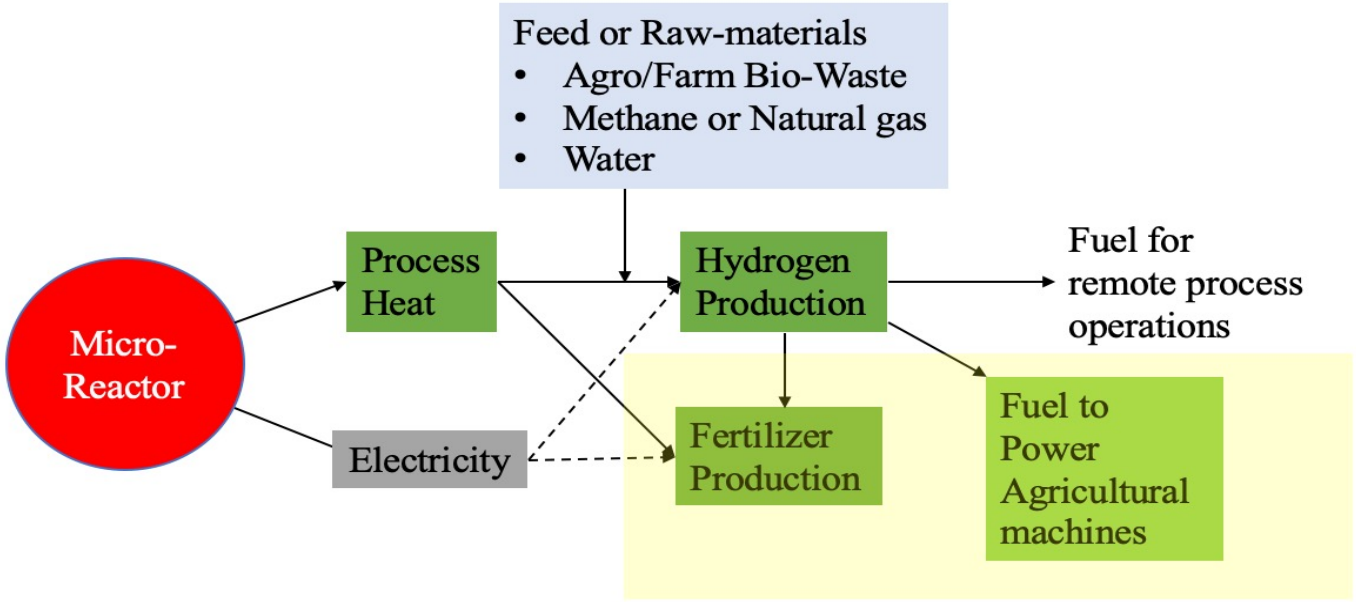
Mark Ruth (Co-PI), NREL

- Students

Zayed Ahmed (Graduate student)

Bailey Strine (Graduate student)

Anshuman Chaube (Graduate student)



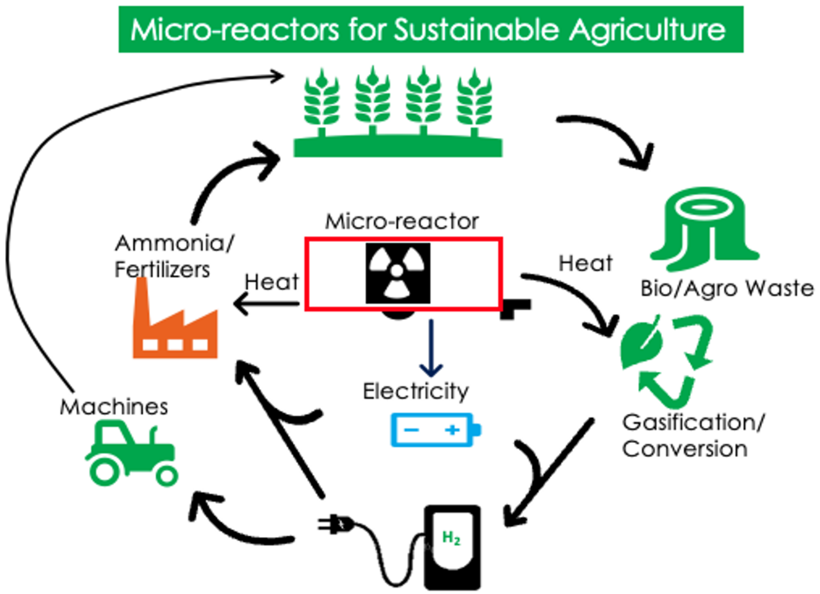
Start Date: Oct. 2021

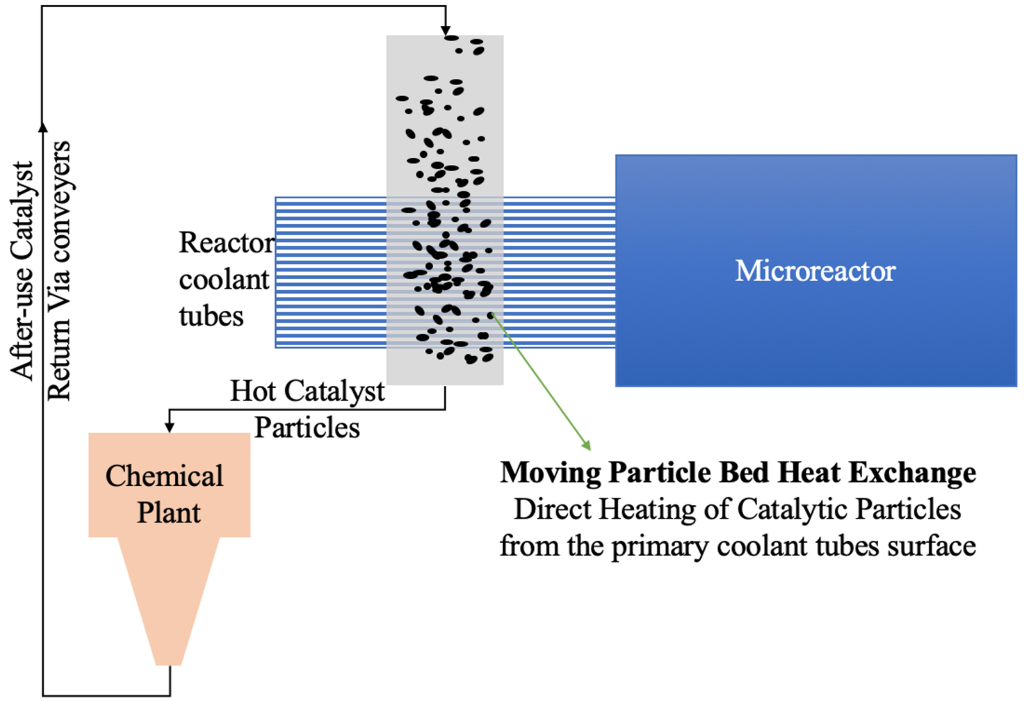
MRP Microreactor Program

Direct heating of chemical catalysts for hydrogen and fertilizer production using Microreactors

Project Objectives

1) Design MPBHX and compare other IHX alternatives for microreactor integration.
2) Exergy and techno-economic feasibility of microreactor integration for hydrogen production and ammonia/fertilizer production.
3) Investigate feasibility of microreactors for achieving sustainable agriculture.





- Moving ceramic particles have high volumetric heat density.
- Store heat for later use.
- Catalyst carriers to sustain thermochemical reactions

MRP Microreactor Program

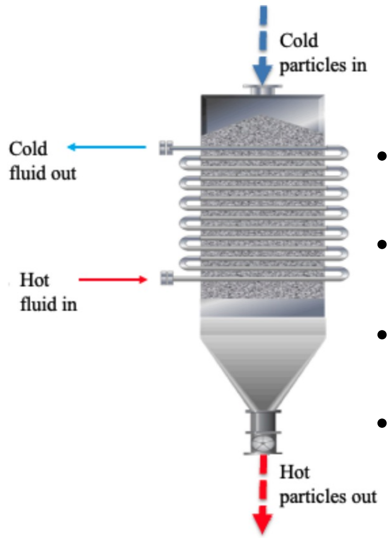
Project Timeline

Milestone	End Date
MPBHX concept design with calculations	9/30/22
Microreactor end-use compatibility	9/30/22
Design matrix and comparative analysis for different microreactor integration concepts	6/30/23
Hydrogen production potential	9/30/23
Overall MPBHX integration economic assessment	4/30/24
MAGNET demonstration guidelines	5/30/24
Sustainable agriculture-case study report	6/30/24

In-Progress

MRP Microreactor Program

Moving Packed Bed Heat Exchanger (Design and Evaluation)



- Gaseous coolants-High Pressure drop-High parasitic Losses.
- Not too many liquid coolants compatible
- Ceramic granular flow – simple design
- Compare options

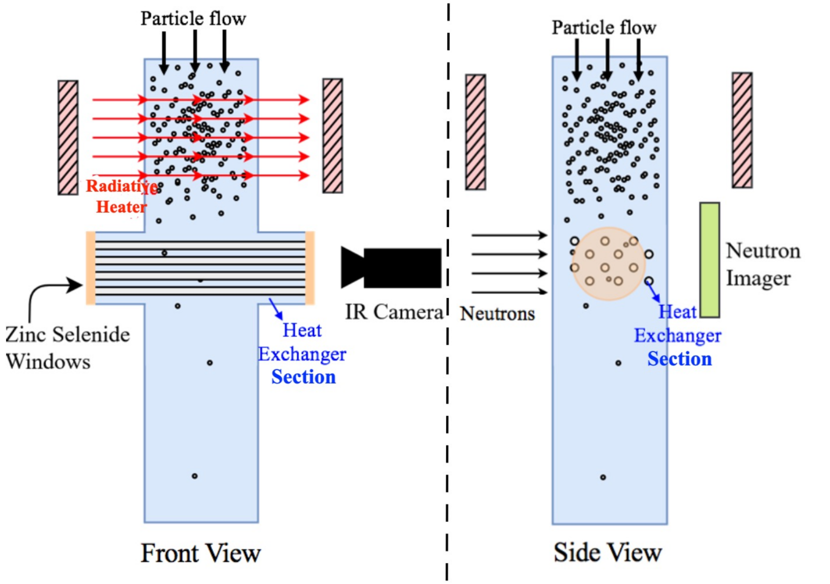
	FOM_ht[1]	FOM_pumping
Air	0.07	40,000
Helium	0.12	25,000
Molten-Salt (Chloride)	0.55	15
Packed bed	0.31	12.5

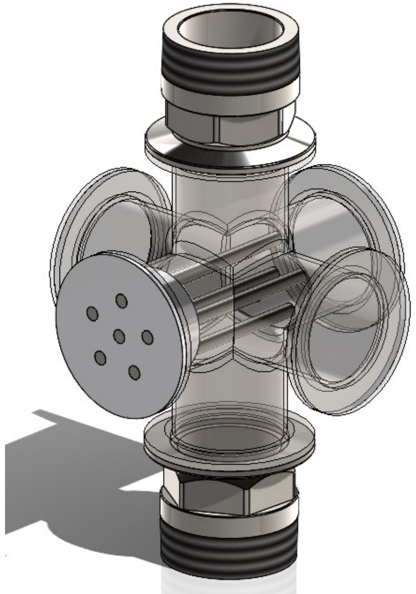
Evaluation Plan

Particles will be flown over electrical heater bank

Thermal imaging response via IR transparent windows

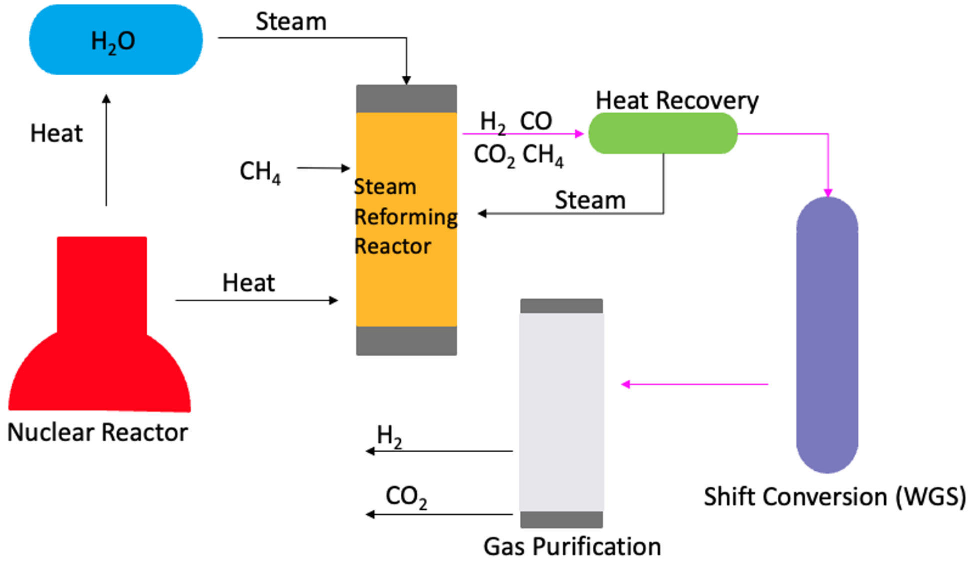
X-ray imaging of particle distribution





[1] Sabharwall et al., INL/EXT-11-21584

Hydrogen production using Microreactors



Replacing the standard Methane fueled heat supply with microreactor heat

JAEA HTTR (10 MW th) is used for baseline analysis

Steam Methane Reforming- Thermochemical process at 700- 800ºC

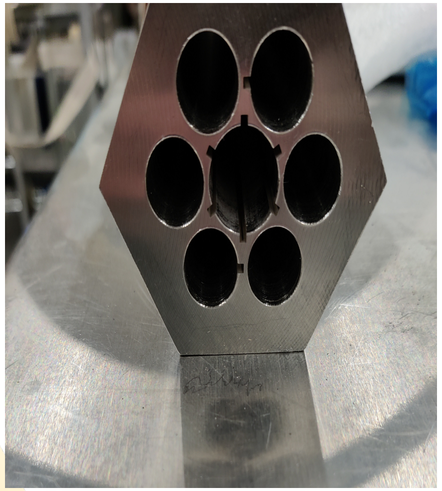
Source of Emissions	CO_2 emissions (Standard)	CO_2 emissions (Nuclear)
Conversion of feed to hydrogen	0.75 kg/s	0.75 kg/s
Combustion for reforming reaction	0.19 kg/s	N/A
Combustion for steam production	0.28 kg/s	N/A
Total Emissions	**1.22 kg/s**	**0.75 kg/s**

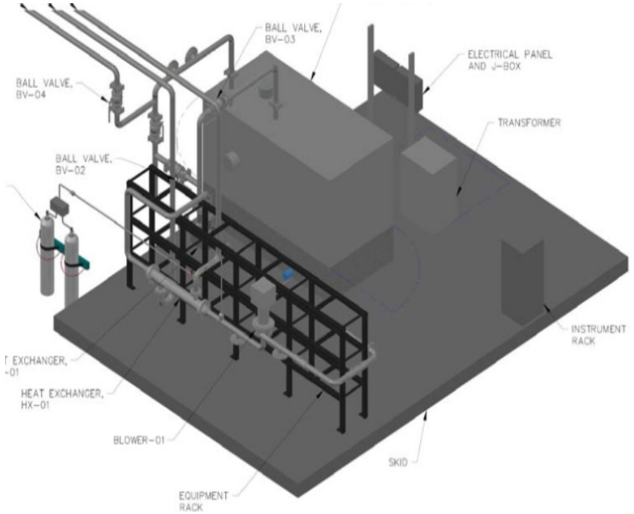
Just replacing the heat component with Nuclear heat can reduce carbon emissions by 38%

MRP Microreactor Program

DOE-NE Microreactor Program Winter Review Meeting

Demonstration Capabilities Overview – Summary

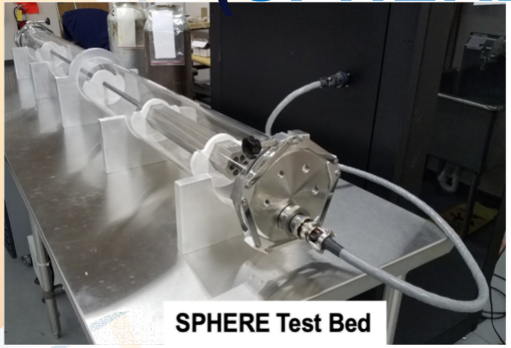




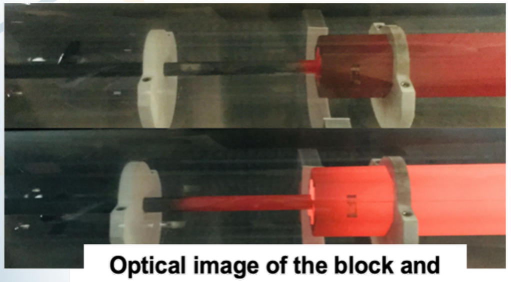
March 4, 2022

Piyush Sabharwall, Ph.D. | Technical Area Lead

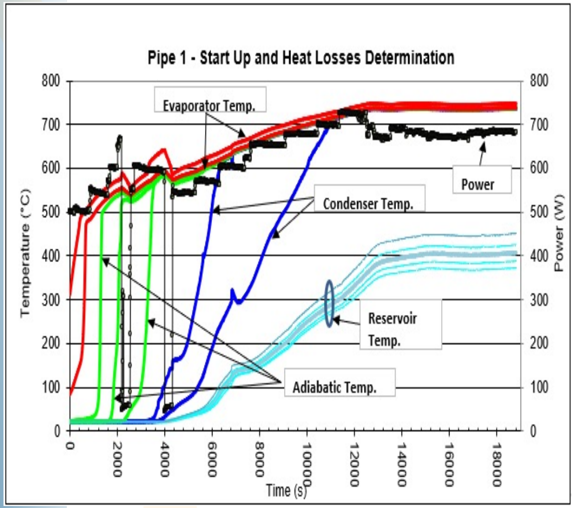
Single Primary Heat Extraction and Removal Emulator (SPHERE)



SPHERE Test Bed



Optical image of the block and heat pipe operation



Objectives

- Provide **capabilities** to perform steady state and transient testing of heat pipes and heat transfer:
  - Wide range of heating values and operating temperatures
  - Observe **heat pipe startup and transient operation**
- **Measure** heat pipe axial temperature profiles during **startup, steady-state, and transient operation** using thermal imaging and surface measurements

Parameter	Value
Length	243 cm
Diameter	15 cm
Tube material	Quartz
Connections	Flanged for gas flow and instrumentation feed through
Maximum power	20 kW
Max Temperature	750 C
Heat Removal	Passive radiation or water-cooled gas gap calorimeter

Key Accomplishments

- SPHERE Initial Startup and Operation
- Complete Engineering Design of Gap Conductance Test Article
- Working Closely with DOE-NEAMS Prog to Jointly Support V&V Activities

In Progress

- Ongoing modifications for SPHERE facility
- Gap Conductance Testing for NRC
- Understanding the effect of orientation on heat pipe performance (Work for Others – Industrial Partner)

Challenges

- Testbed chamber is inadequate for accessibility and assembly
- TC routing too tight
- Secondary test article creates additional complexity
- Contact resistances are significant source of model error

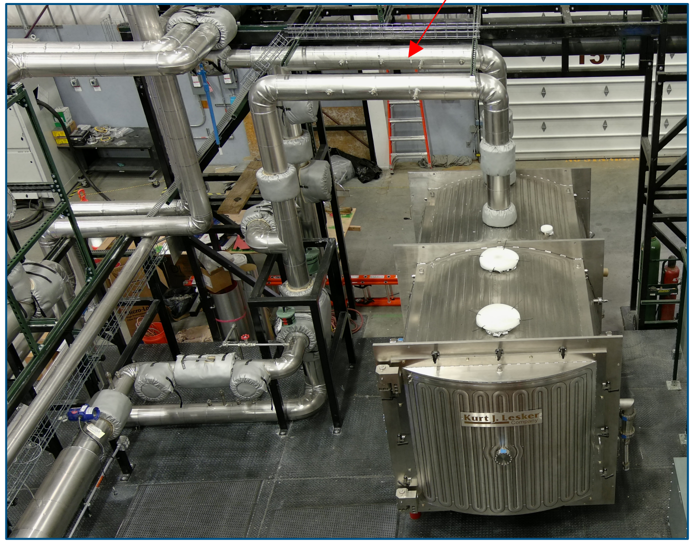
MRP Microreactor Program

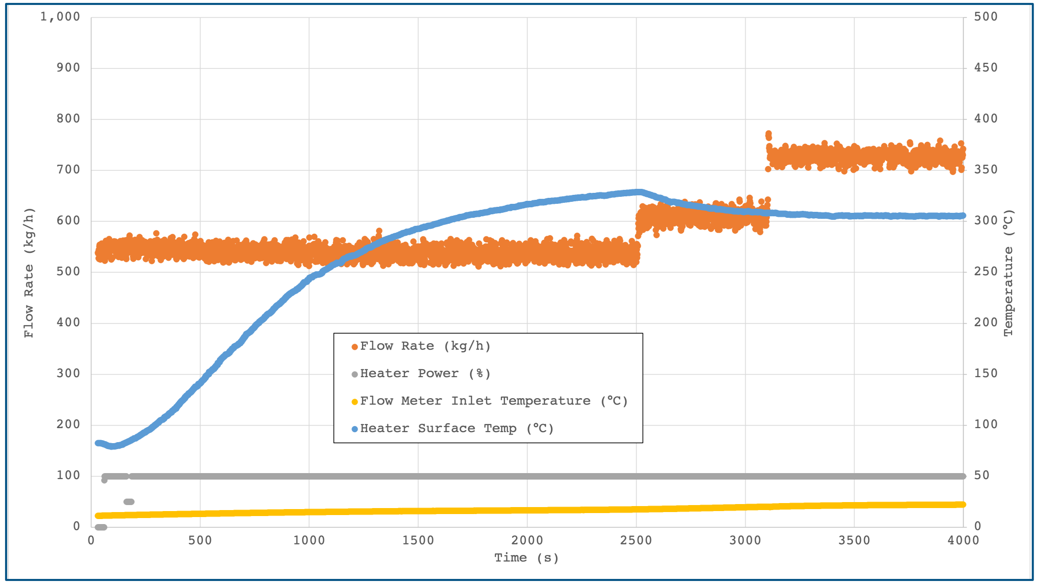
MAGNET Accomplishments

- Completed construction in November 2020
- Pressurized, started, and slightly heated system in January of 2021 for ASME B31.3 pressure testing
- A change in Engineer of Record for design and construction resulted in removal of insulation from all joints for a new B31.3 pressure test
- Discrepancy between installation drawings and as-built drawings resulted in removal of a section of piping to weld in a thermal expansion loop.

- Final pressure testing of reworked section of piping

Thermal expansion loop added to this section



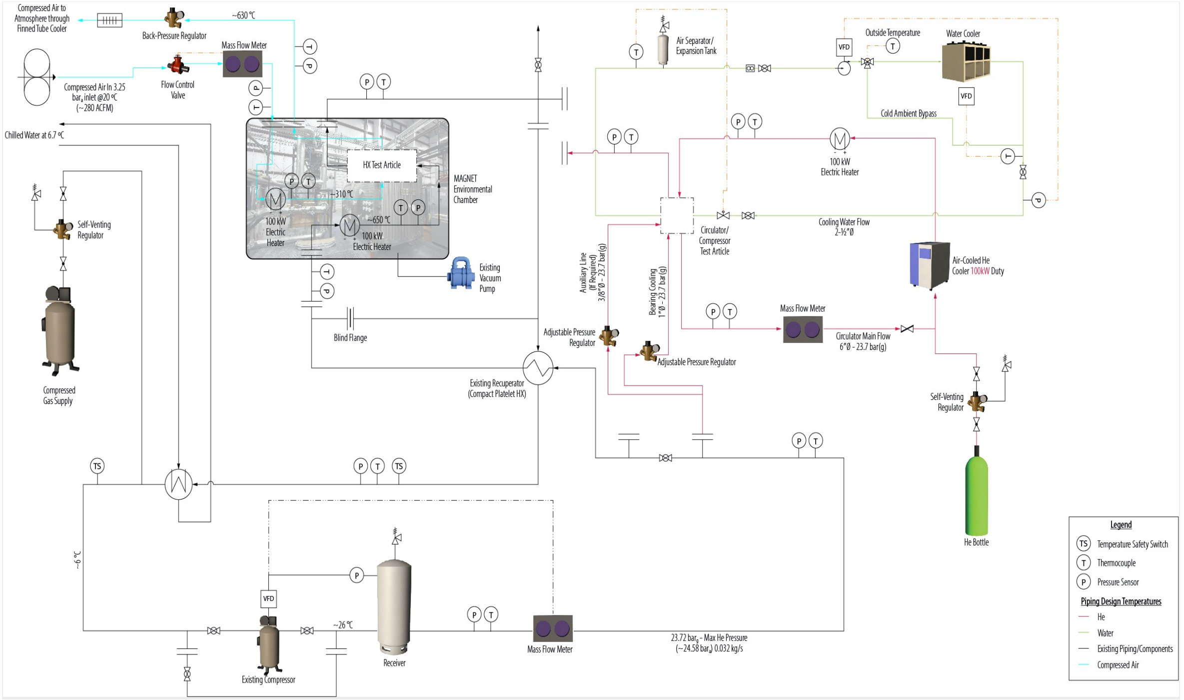


Startup Data

MRP Microreactor Program

Ongoing Modification for MAGNET – He Component Test Facility

- Gas cooled reactors have been proposed to support several funded reactor demonstration projects. Most inert gaseous coolants such as Helium, Argon and Nitrogen are low molecular mass fluids and can be difficult to work with. Most design processes require that components be qualified to a **TRL of 6** prior to integration with a system. A test facility, or series of facilities is necessary in order to characterize and qualify critical reactor components in high-temperature flowing environments.
- The need to test full scale control drums, control rod assemblies, heat exchangers, pumps and re-circulators have been identified in discussion with reactor vendors. Currently no known facilities can accommodate these testing needs, especially for long duration reliability testing.
- Establishment of a Helium Component Test Facility (He-CTF) will support the development and deployment of advanced gas cooled reactors and technologies.



MRP Microreactor Program

Potential Areas Where Industry Can Leverage SPHERE and MAGNET (Non-Nuclear Test Bed)

- Heat Pipe Thermal Performance
  - Startup and Shutdown
- Studying Cascading Failure and Its Effect
- High Temperature and Pressure Testing
  - Prototype microreactor design testing
  - Component Testing
- Instrumentation and Control
  - Advanced Manufactured Test Articles
  - Advanced Manufacturing Sensor Development
- Verification and Validation
  - Concepts with low TRL levels for better understanding
  - Addressing Technical Gaps and Data Requirement
- Interface and Coupling Different Systems
  - Heat Exchanger
  - PCU Integration
- Safety Basis
  - Design Margins

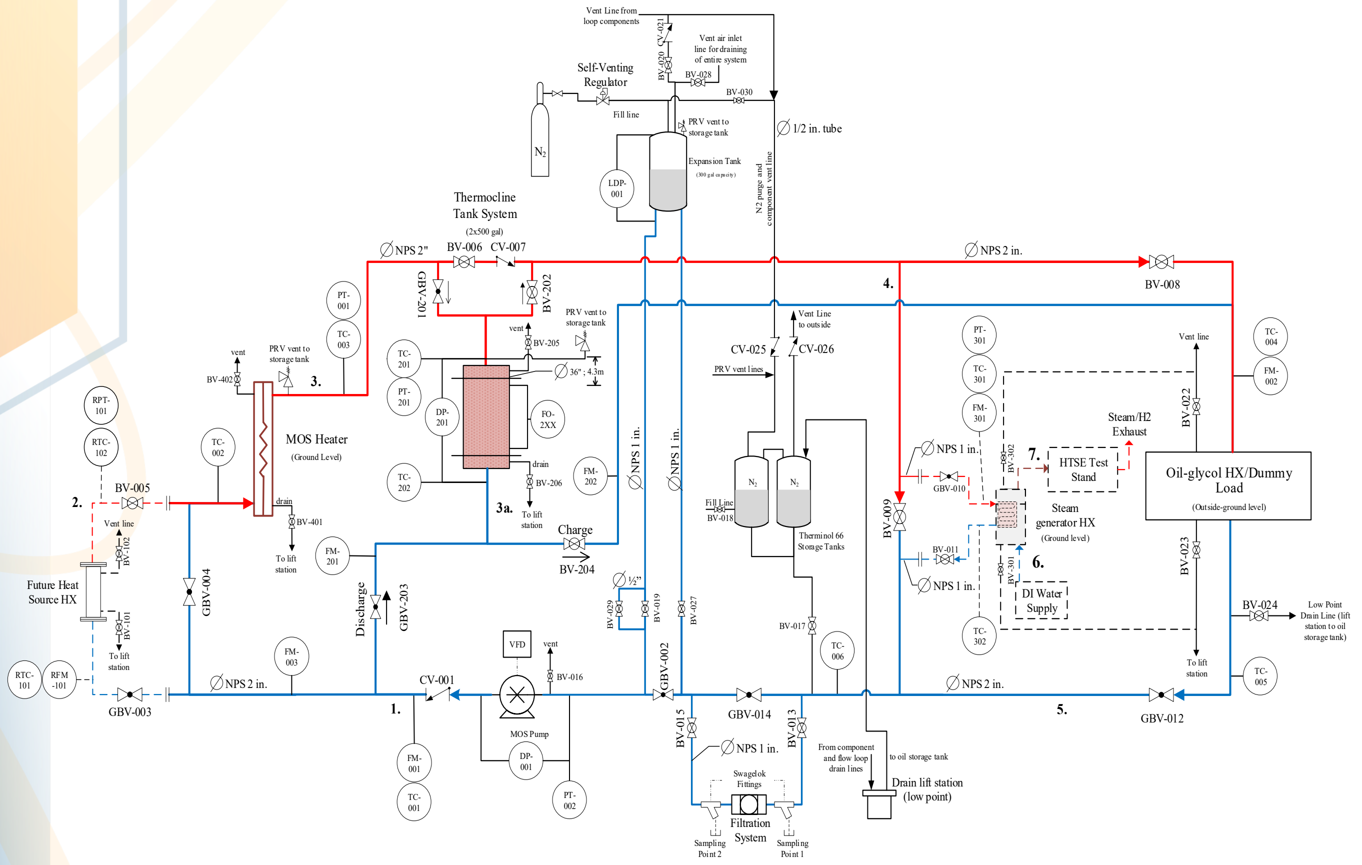
MRP Microreactor Program

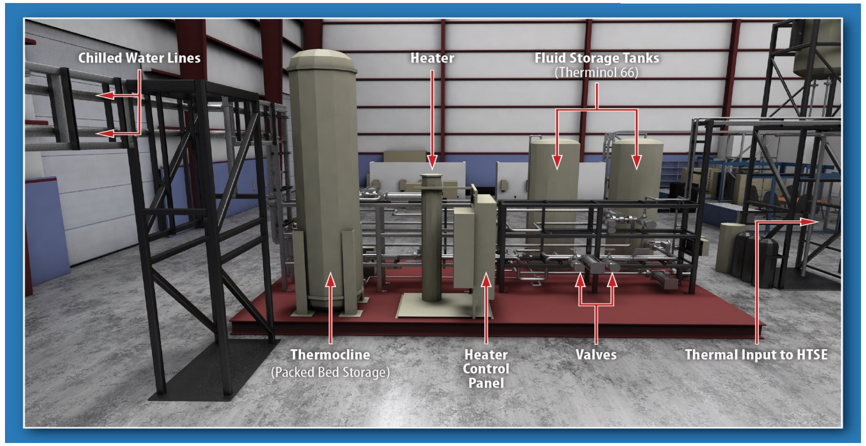
MAGNET Facility

- MAGNET Deployment in the INL Energy Systems Laboratory (ESL) building, Systems Integration Laboratory
- Co-located with the Thermal Energy Distribution System (TEDS) and the High-Temperature Steam Electrolysis (HTSE) System

Thermal Energy Distribution System (TEDS)

IES
Integrated Energy Systems



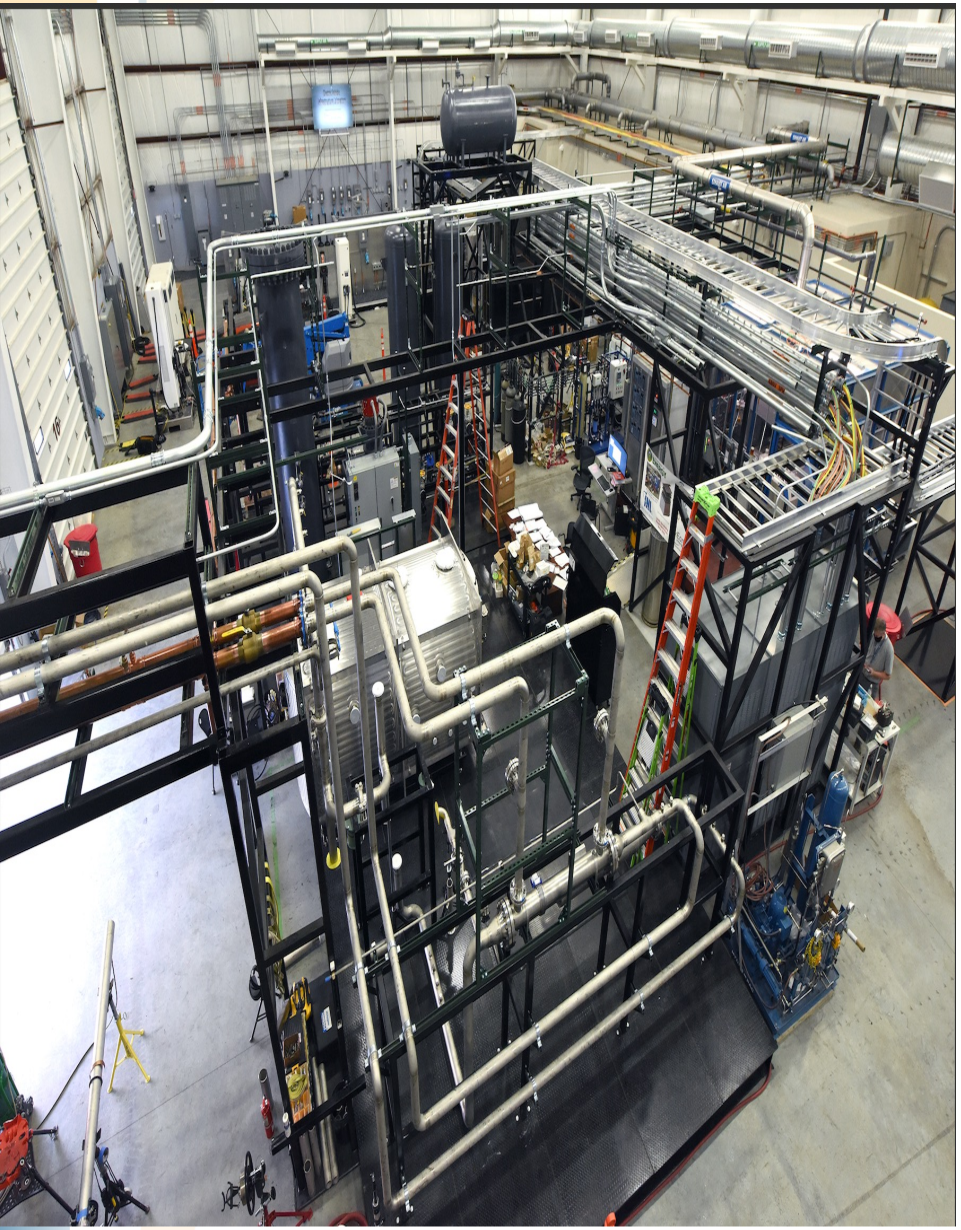


Condition	Value
Design Pressure	100 [psig]
Design Temperature	340[°C]
Maximum Oil Operating Temperature	325[°C]
Return Oil Operating Temperature	225[°C]
Maximum Operating Pressure	14 [psig]
Nominal flow rate	0.8-1.62 [kg/s] (14-33 [gpm])
Nominal Pipe Size (NPS)	2 [in.]

- Thermal network for transport of heat from thermal energy sources to thermal energy “customers”
- Independent thermal energy source; controllable heater (200kW)
- TEDS is designed with multiple flanges for future ancillary application connection

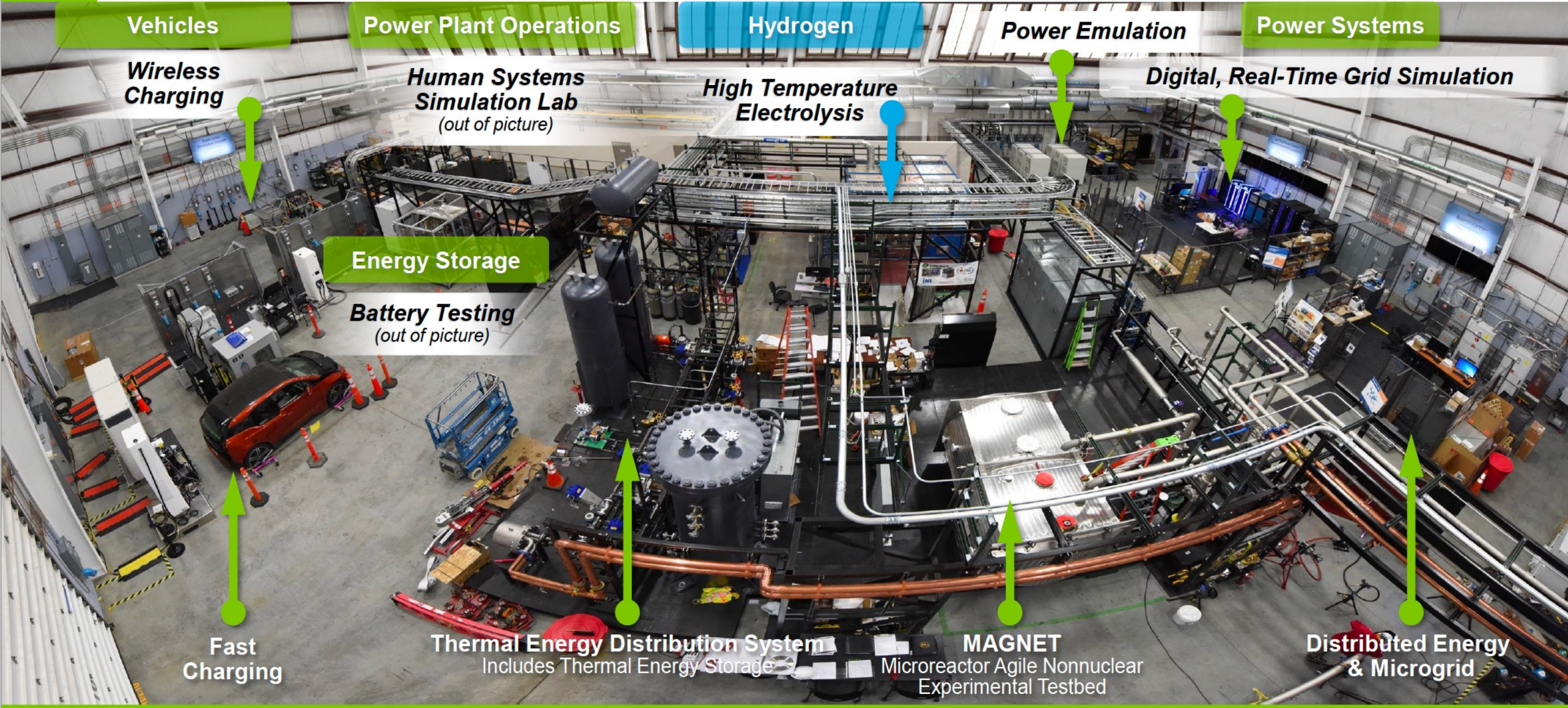
MAGNET Facility - Pics

INL Energy Systems Laboratory (ESL) building, Systems Integration Laboratory



MAGNET & Co-Located Systems

Integrating systems for the nation's net-zero future



Main Conclusions

- Working closely with other DOE Programs to leverage and support joint efforts
- Regular interaction with industry through programs such as NRIC (ARDP funded projects)
- Interaction with Academia through DOE-NEUP program
- Bi-Monthly Meetings with PI's of NEUP's who are involved in experimental work
- This area did experience procurement delays due to pandemic, which did effect completion dates of milestones
- Successful demonstration are needed to gain utility, regulator, and public confidence.

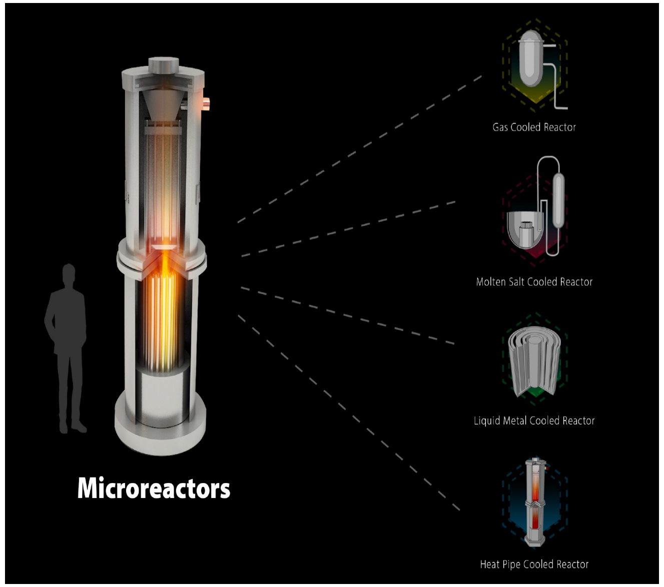
Path Forward

SPHERE

- Completion of gap conductance testing
- Heat Pipe performance at different orientations, supporting industry needs
- V&V support for Sockeye

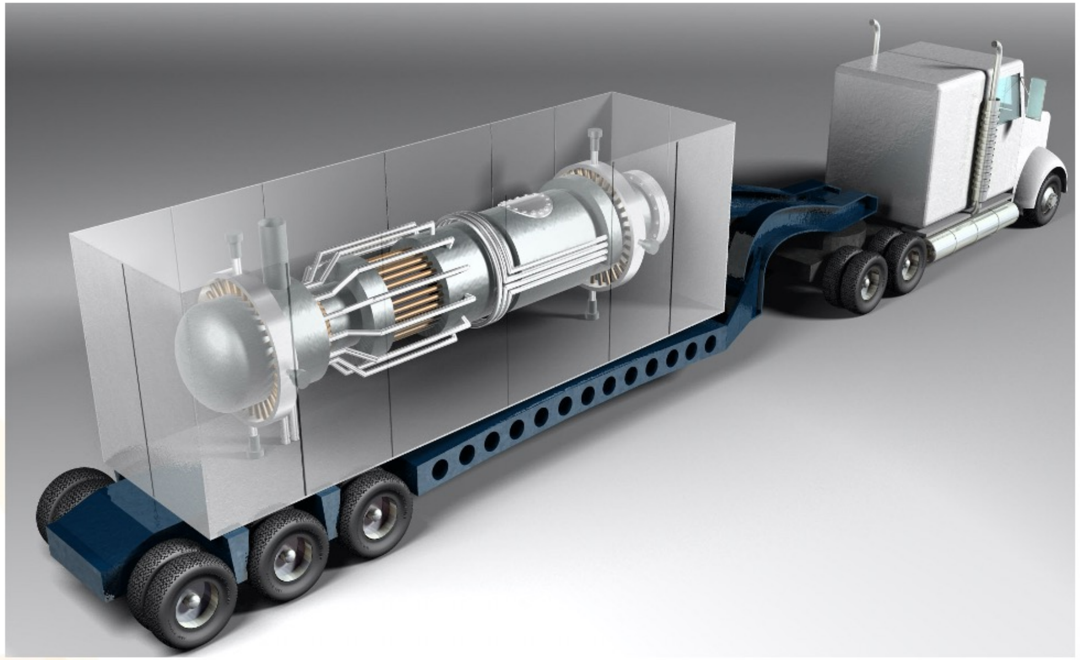
MAGNET

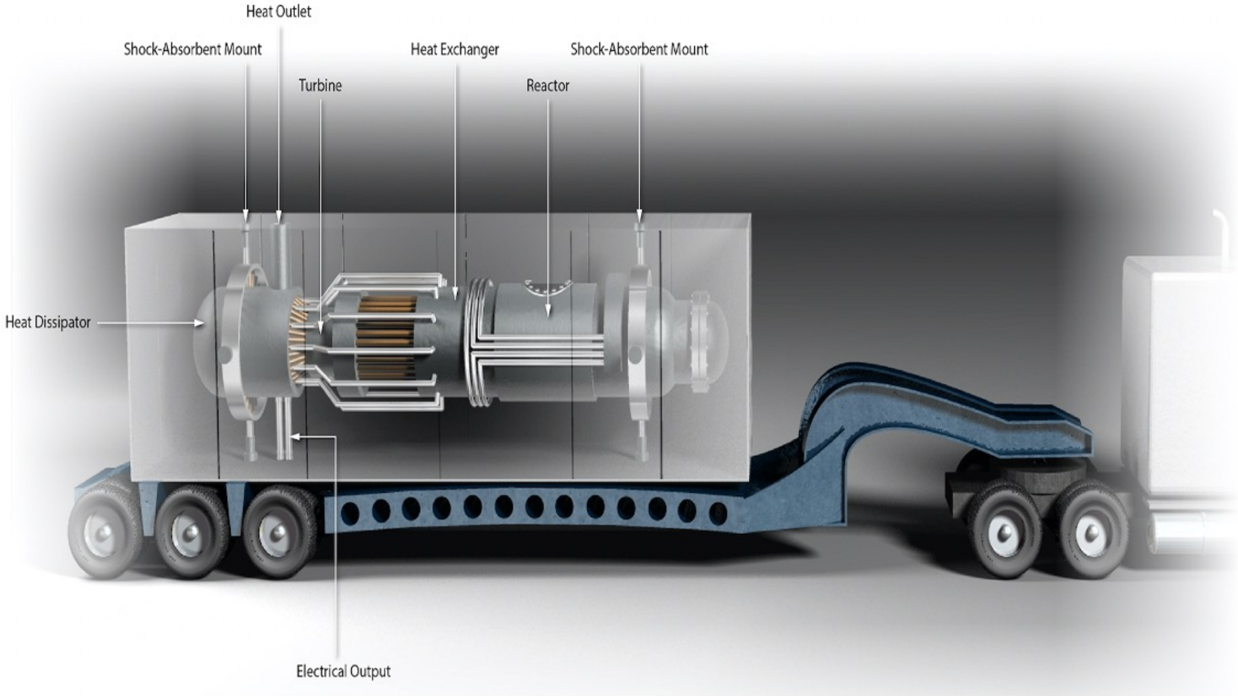
- Complete Single Heat pipe Test Campaign
- High Temperature Component Testing (HX, Circulator,.. Supporting industry needs)
- Installation of 75 kW (37 Heat Pipe) Test Article



MRP Microreactor Program

Thank You..!





Piyush.Sabharwall@inl.gov

Credit & Acknowledgement

U.S. DEPARTMENT OF ENERGY Nuclear Energy

Idaho National Laboratory NS&T | MFC

Los Alamos NATIONAL LABORATORY EST.1943

Oak Ridge National Laboratory

Argonne NATIONAL LABORATORY

MRP Microreactor Program